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DMIC Report 179
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# A GUIDE TO THE LITERATURE ON HIGH-VELOCITY METALWORKING



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DMIC Report 179
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# A GUIDE TO THE LITERATURE ON HIGH-VELOCITY METALWORKING*

by

D. E. Strohecker and D. H. Owens

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

*Documents listed in this bibliography are not available from the Defense Metals Information Center. Requests for documents not available through libraries should be referred either to the Office of Technical Services, Washington 25, D. C., or the Armed Forces Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia.

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## TABLE OF CONTENTS

## TABLE OF CONTENTS
(Continued)

# PREFACE

This report is an up-dating and thorough revision of a bibliography prepared previously as an activity of the U. S. Army Reserve 2396th Research and Development Unit in Columbus, Ohio. That previous bibliography was designated as Report NA62H-46-ORD-241 and as ASTIA Document AD 276693.

The author would like to express appreciation to The Columbus Division of North American Aviation, Inc., for its assistance in the preparation and reproduction of the initial reports leading to this bibliography.

The efforts of the following personnel who have assisted in the collection and organization of the data from time to time are also acknowledged.

| | |
|---|---|
| Hugh D. Hanes | Harry C. Loudenslager |
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| Allen H. Clauer | Robert J. Metzger |
| Patricia B. Plate | Walter H. Veazie, Jr. |

# A GUIDE TO THE LITERATURE ON HIGH-VELOCITY METALWORKING

## SUMMARY

This report is a guide to the literature on high-velocity metalworking. It consists primarily of abstracts of articles, reports, books, and current research projects on and related to high-velocity metalworking arranged according to technical subject. It covers a survey of the reported work in the field up to about October of 1962. Abstracts of over 700 references have been arranged by subject matter, with cross indexing between subjects. There is also an author index.

The eleven major subjects and categories covered in the report are: (1) Energy Sources, (2) Energy Transfer Mediums, (3) Facility Requirements, (4) Tooling Requirements, (5) Equipment Requirements, (6) Forming, (7) Hardening, (8) Explosive Welding, (9) Powder Compaction, (10) Metal Removal, and (11) Material Behavior.

The references are further categorized by materials under the specific processes where it is believed this will help the user.

## INTRODUCTION

The term "high-velocity metalworking" is now being used in place of the former nomenclature "high-energy-rate metalworking" since many new and conflicting processes have now expanded so that the earlier title has lost its descriptive meaning. A simple definition of high-velocity metalworking might be this: any process which works materials at a velocity which exceeds that generally available in conventional metalworking equipment. This means, roughly, a working velocity greater than 30 ft/sec.

For purposes of orientation, high-velocity-metalworking technology is summarized in Tables 1 and 2. Inevitably, in such a drastic summary, some of the entries will be debatable, as they depend to a great extent on the method of operation and even to some extent on point of view. In spite of any shortcomings, the table is worth presenting if only to stimulate debate and thereby help lead to a more realistic approach for future analysis of high-velocity-metalworking technology.

As noted in the Preface, this report supersedes Report NA62H-46, ORD-241 (ASTIA AD 272693) in its entirety. It includes all the abstracts in the previous report plus many new additions. The previous report covered mainly past published literature. This report expands that previous coverage to include more recent items, especially those emanating from current Government-sponsored development programs.

Compiling this report has been the first step in preparing a comprehensive report on the state of the art in high-velocity metalworking. The Defense Metals Information Center soon will publish a state-of-the-art summary on explosive forming of sheet-metal parts.

Most of the articles abstracted in this report apply directly to the process of high-velocity metalworking, while some have only indirect applicability. Some of the abstracts were prepared by the author or others in the Defense Metals Information Center. In other cases the original author's abstract was used. The abstracts are assembled into groups according to their main topics. In addition, they are cross indexed when they deal with more than one subject. The subject arrangement used can be seen in the Table of Contents, along with the coding system followed. The arrangement is based on metalworking considerations. Thus, parallel subsections on each important type of alloy appear in the several metalworking-process sections.

This report is intended to be a working document. Only publications which would be easily available to industry are included, although more references had been found which might have been included for academic completeness.

Supplements to this report may be issued from time to time, when the activity in high-velocity metalworking warrants, as DMIC continues to function as a centralized source of information on high-velocity metalworking.

TABLE 1. HIGH-VELOCITY-

| | High Explosive | Propellants | Gas Mixtures |
|---|---|---|---|
| **Source Characteristics** | | | |
| Method of Energy Release | Chemical detonation | Chemical burning | Chemical burning |
| Medium of Operation | Water-sand-air-plastics | Air-water | Gas |
| Rate of Energy Release | Medium to very fast<br>4,000-25,000 ft/sec | Slow to medium<br>1,000-8,000 ft/sec | Slow to medium<br>1,000-8,000 ft/sec |
| Speed of Material Deformation | 50-200 ft/sec | 50-200 ft/sec | 50-200 ft/sec |
| **Adaptability** | | | |
| Time Required to Place a New Facility into Operation | None | None | 4 months |
| Availability of Equipment | Excellent | Good | All equipment is presently in-house fabricated |
| Elevated-Temp Capabilities | Poor | Poor | Fair |
| Location of Facility | Remote | Separate | Separate |
| Part-Size Limitations | None | Limited by size of a closed container which will hold the pressure (5 ft dia. max) | |
| **Versatility** | | | |
| Part Shapes Obtainable | Good | Poor | Fair |
| Uses for Technique Reported to Date | Blanking, coining, powder comp., cutting, embossing, drawing, expanding, flanging, hardening, joining, sizing, stretching, inspection | Bulging, compacting, sizing, stud driving, machining | Bulging, sizing, stretching |
| **Process Selection Factors** | | | |
| Main Advantage | Part-size capability | Hand tool | Close tolerances on thin parts |
| Capital Investment | Low to medium | Low | Medium |
| Tooling Costs | Low | Medium | High |
| Operating Costs | High | Medium | High |
| Energy Costs | High | High | Low |
| Cycle Time Present | High | Medium | High |
| Cycle Time Future | Medium | Medium | Medium |
| Special Considerations of Safety | Only personnel trained and competent in the application of explosives and propellants should operate | | Only technicians with complete knowledge of exploding gas mixtures |
| **Areas Still Requiring Development** | | | |
| Practical | Development of quick-acting hold-down rings<br>Standardization of charges<br>Distribution of practical process and design information<br>New tooling methods for very large dies<br>Elimination of the use of blasting caps | Development of reproducibility<br>Operation in an unconfined environment | Methods of operating in an unconfined environment<br>Mixture control<br>Design of chambers for consistent firing |
| Theoretical | Effect of high strain rates on the properties of metals and alloys<br>Development of new thermal treatments in conjunction with the high-strain-rate deformation<br>Development of a theoretical analysis for high-energy-rate die design<br>Development of a theoretical analysis for high-energy-rate deformation and formability of materials<br>Investigation of shock-wave attenuation in various mediums | | |

METALWORKING STATE OF THE ART

| High-Pressure Gas | Electric Discharge | | Magnetic Field |
|---|---|---|---|
| | Exploding Wire | Spark Discharge | |
| Expansion of gas | Vaporization of wire | Ionization of medium | Collapsing magnetic field |
| Air | Water-air | Water-air | Air |
| Slow | Fast to very fast | Fast to very fast | Medium to fast |
| 50-200 ft/sec | 20,000 ft/sec | 20,000 ft/sec | 10,000-20,000 ft/sec |
| 50 to 200 ft/sec | 50 to 200 ft/sec | 50 to 200 ft/sec | 50 to 200 ft/sec |
| 2-6 months | 6 months | 6 months | 8 months |
| Excellent | Good | Good | Fair |
| Excellent | Good | Good | Fair |
| Unrestricted | Separate | Separate | Separate |
| Present: 18 in. dia. part | Present: 5 ft dia. part | Present: 5 ft dia. part | Present: 12 in. dia. part |
| Future: 36 in. dia. part | Future: 10 ft | Future: 10 ft dia. | Future: 4 ft dia. |
| Excellent | Good | Fair | Fair |
| Compacting, drawing, extruding, forging, stretching, upsetting | Bulging, stretching | Bulging, stretching | Swaging, joining, shrinking |
| Forging and extrusion | Reproducibility | Simplicity | Swaging-Type operations |
| Medium to high | High | High | High |
| Medium | Medium to high | Medium to high | High |
| Low | Medium | Medium | Medium |
| Medium | Low | Low | Low |
| Low | High | Medium | Medium |
| Very low | Low | Low | Low |
| Conventional guards and interlocking switches, as with presses | Restricted access and safety interlock required as with all high tension equipment | | |
| New tooling concepts<br>New tooling materials<br>Methods for slowing extrusions<br>Larger capacity<br>Automation of Equipment | Automation<br>Better electrical switching devices<br>Reduction in cost of capital equipment | Development of electrodes which will withstand the force<br>Better control of discharge characteristics<br>Reproducibility<br>Automation | Development of designs for permanent coils<br>Development for use on parts other than tubing |

# ABSTRACTS

## Energy Sources

### Chemical A-1-0

Heilveil, Sidney, "Safety and High Energy Rates", ASTME Technical Report No. SP60-103 for presentation at the Creative Manufacturing Seminars (1960-1961). A-1-0-1

The safety of high-energy-rate operations is considered in detail for each of the various energy sources. A number of safety precautions to be taken prior to, during, and after closing down an operation are covered in detail. This report is well worth reading for anyone contemplating entering into the high-energy-rate forming field.

Sabroff, Alvin M., "General Aspects of High-Velocity Forming", ASTME Technical Paper No. SP62-71, presented at the Creative Manufacturing Seminars (1960-1961). A-1-0-2

A general review of the characteristics of various high-energy-rate sources is given and compared with conventional forming equipment. Numerous methods of using the energy and specific applications for each are mentioned. Specifics of the operations and process information were not discussed.

Sabroff, Alvin M., "Status of High-Energy-Rate Forming", ASTME Report No. SP62-01, presented at the Creative Manufacturing Seminars (1961-62). A-1-0-3

This paper reviews the state of the art in explosive forming and other high-energy-rate methods of metalworking. The paper identifies areas where information is still lacking and additional research work will be required. The effect of high-energy-rate metalworking techniques on the material properties is one of the areas where considerable effort is still required. While some methods have moved out of the laboratory into production, new areas have been opened for investigation.

Wood, W. W., "A Critical Review of High Energy Forming", Final Report AER/ME/OR-5-3, Chance Vought Aircraft (January 19, 1960). A-1-0-4

This report covers the entire field of high-energy-rate metalworking. It deals with the classification and description of basic energy types, theory of plastic deformation of metals, energy comparisons, limitations, and applications. Attempts are made to compare the high-energy-rate techniques with conventional forming methods. Numerous equations are presented relating energy to the formability of various materials. The effect of strain rate on the deformation of materials is also discussed.

Wood, W. W., "A Critical Review of High-Energy Forming Methods", ASTME Technical Paper No. 292, Vol. 60, Book 1. A-1-0-5

An attempt is made to show the limitations and applications of each high-energy system based upon very fundamental concepts in the plastic deformation of metals. Explosive forming is emphasized because of the great amount of data available on this system. Materials examined include semiaustenitic stainless steels, martensitic stainless steels, tool steels, beryllium, super alloys, and refractory metals. Information as to their response to high-velocity forming and recommendations as to use are given. Indications of increased ductility have been observed in connection with the use of new techniques.

"How You Can Use High Energy Rate Forming", Steel, 146 (17), 108-111 (April 25, 1960). A-1-0-6

This is a nontechnical report for managers who want the latest word on four new processes: explosive forming, hydroelectric forming, pneumatic-mechanical forming and closed-cavity extrusion molding.

Encyclopedia of Explosives, Ordnance Technical Intelligence Agency, Durham, North Carolina (May 13, 1960); AD 274026. A-1-0-7

This is a compilation of principal explosives, their characteristics, processes of manufacture, and uses. It covers both United States and foreign explosives.

Ezra, A. A., and Penning, F. A., "Development of Scaling Laws for Explosive Forming", Experimental Mechanics, 2 (8), 234-239 (August, 1962). A-1-0-8

Explosive forming is potentially a fast and economical process suitable for large sheet metal shapes used in boosters or spacecraft. However, the development of an optimum technique with a particular material is a trial-and-error process. With reliable scaling laws, this trial-and-error process can be carried out conveniently and inexpensively on a small scale. This study develops workable scaling laws and shows what similitude requirements may be neglected in a scale-model test.

Cross References.

A-3-0-1 Discusses all forms of high-energy forming methods including high-mass systems, high-velocity systems, and high-temperature systems.

E-2-19 A study on deflagration and detonation in propellants and explosive.

F-1-0-115 Derives equation for calculating gas pressure produced by the explosion of an ammonite ball.

Chemical

High Explosives. A-1-1

Birkhoff, Garrett, MacDougall, Duncan P., Pugh, Emerson M., and Taylor, Sir Geoffrey, "Explosives with Lined Cavities", Journal of Applied Physics, 19 (6), 563-582 (June, 1948). A-1-1-1

A mathematical theory is presented dealing with lined cavities to indicate the enormous increase in penetrating power over unlined cavities. The historical background, covering the past century, is presented with experimental data. The theory is divided into two phases: the first deals with the formation of the metal liner into a long thin jet traveling longitudinally at very high velocities (30,000 feet per second); the second deals with the forcing aside of the target material by the extremely high pressures (0.3 million atmospheres) produced by the impact of the high-speed jet. The theory is based upon classical hydrodynamics of perfect fluids which is applicable since metal strength can be neglected at the high pressures encountered.

Bowden, F. P., and Yoffe, A. D., Initiation and Growth of Explosives in Liquids and Solids, Cambridge University Press, New York (1962). A-1-1-2

The book covers a study of the mechanisms of initiation of explosives. For the majority of explosives this initiation is thermal. The thermal energy may be supplied by adiabatic compression of entrapped air bubbles, by frictional hot spots formed, and extreme heating of the rapidly-flowing explosive as it escapes from between impacting surfaces. The book also discusses experimental techniques for proving the proposed theories.

Boulger, F. W., "Metal Forming Problem? Try H.E.R. Techniques", Mechanical Engineer, 84 (4), 38-73 (April, 1962). A-1-1-3

This article presents a comparison of the relative-energy-output ratings, on the basis of foot-pounds per second, for the various energy sources: explosives, electro-spark devices, pneumatic-mechanical devices, hammer and press, in decreasing order of output capabilities. Some of the unusual characteristics of each system are listed and some of the techniques presently being used in their application to production and research are given. The effects of shock loading on iron and columbium are discussed.

Carlton, C. H., Warren, F. A., and Wiegand, J. H., "The Industrial Use of High-Energy Materials", Chemical Engineering Progress, 51 (7), 335 (1955). A-1-1-4

This article presents a review of common explosives, the quantities produced in USA, and their general usage. Explosive forming of metal is treated in very general terms.

Cole, Robert H., Underwater Explosions, Princeton University Press, Princeton (1948). A-1-1-5

This book covers the unclassified theoretical and experimental work conducted before 1948 on underwater explosions. The following topics are discussed: the sequence of events in underwater explosions, hydrodynamical relations, the detonation process in explosives, theory of the shock wave, measurement of underwater explosion pressures, photography of underwater explosions, shock wave measurements, motion of the gas sphere, secondary pressure waves, and surface and other effects.

Although this book deals primarily with larger charges and greater depths than would be used in high-energy metalworking the scaling effect may be used with a fair degree of reliability.

Davidson, S. H., and Westwater, R., "Shaped or Hollow Charge", Mine and Quarry Engineering, 15 (5), 140-145 (May, 1949). A-1-1-6

This bulletin covers the history of the development of explosives from the development of dynamite by Alfred B. Nobel to the present production of high explosives. The destructive force of the explosives was at first uncontrollable and many accidents were experienced before safe types of explosives could be discovered. Although high explosives were first used as a destructive force in war the peace time uses are now consuming more than was previously used in warfare.

Cook, Melvin A., The Science of High Explosives, ASC Monograph No. 139, Reinhold Publishing Corporation, New York (1958). A-1-1-7

Detonation processes and related phenomena are described with theoretical interpretations and illustrations. Results of research on initiation, wave structure, propagation, the nature and rates of chemical reactions of detonations, ionization, radiations, and shock and blast waves are presented. Information on demolition, shaped charges, blast wave propagation, impact loading, strength, penetration, and conditions for explosions of material is also presented.

Cook, Melvin A., "The Amazing Story of Explosives", Bulletin of the University of Utah, 42 (7), 140-145 (February 18, 1952). A-1-1-8

This article deals with the Munroe or Newmann effect and the principles of the shaped charge.

Davis, Tenney L., The Chemistry of Powder and Explosives, Vol 1 and Vol 2, John Wiley and Sons, Inc., New York (1943). A-1-1-9

These books contain basic information on the chemistry, history of development, and the methods of manufacture of explosives and propellants.

Eichelberger, R. J., and Pugh, E. M., "Experimental Verification of the Theory of Jet Formation by Charges with Lined Conical Cavities", Journal of Applied Physics, 23 (5), 537-542 (May, 1952). A-1-1-10

The article presents experimental evidence which verifies the assumptions and conclusions of the author's previous theoretical work on explosive jet formation. A graphical method of predicting the shape of the jet and slug at every instant is presented.

Eichelberger, R. J., "Experimental Test of the Theory of Penetration by Metallic Jets", Journal of Applied Physics, 27 (1), 63-68 (January, 1956). A-1-1-11

Experimental measurements of jet velocity and of penetration velocity as functions of depth of penetration are described for lined cavity charges fired into several types of target material and under a variety of experimental conditions. The results show that the hydrodynamic theory of penetration of Pugh, Hill, Mott, and Pack describes the penetration process very accurately in the early stages. Strength of the target becomes an appreciable factor in the later stages, however. A simple modification of the theory is described which appears to account adequately for these strength effects. Some alterations in ideas concerning the mechanism of penetration by the jet after fracture are also described.

Evans, W. M., "Hollow Charge Effect", Institution of Mining and Metallurgy Bulletin (520), p 25 (March, 1950) and (520), 23-33 (May, 1950). A-1-1-12

This article deals with the effects on a target of a thin-metal-lined hollow-shaped charge. On the assumption that the strength of metals can be neglected the theory of the hydrodynamics of perfect fluids has been applied.

Evans, W. M., and Ubbelohde, A. R., "Formational Monroe Jets and Their Action on Massive Targets", Research, 3 (7), 331-340 (July, 1950). A-1-1-13

A description of hollow charges is given. Damage to metal targets as a function of different metal linings of the hollow charges is investigated. Penetration stand-off curves are also presented.

Feldman, J. B., Jr., "Volume-Energy Relations from Shaped-Charge Jet Penetrations", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). A-1-1-14

This paper considers the application of the shaped charge to the study of penetration and crater formation. The value of the shaped charge lies in the fact that it produces a metal jet which has a reproducible energy-velocity relation. The unusual length of the jet when compared with other high-speed particles makes it possible to study the cratering process in more detail than with any other device.

"Machines Turn Violence into Forming Profits", Steel, 151 (6), 64-70 (August 6, 1962). A-1-1-15

The article discusses the latest developments in all four systems of high-energy-rate forming. The four systems are explosive, electrohydraulic, electromagnetic, and pneumatic-mechanical. The proponents of the pneumatic-mechanical devices claim that they can operate with almost production-line rapidity. All four methods show great cost reductions over conventional means. One man claims that the market for high-energy-rate forming equipment will triple by 1963.

Heinemann, Robert W., Schimmel, Robert T., and Lowell, Stanley J., "Explosive Forming of Explosives", Technical Report 2685, Ord Project TW-120, Feltman Research and Engineering Laboratories, Picatinny Arsenal, New Jersey (June, 1960). A-1-1-16

This report describes an investigation of the feasibility of pressing explosives by a modification of the explosive pressing technique. Using this technique, composition A-3 and TNT powders were pressed into pellets having densities as high as 1.66 and 1.61 g/cc, respectively. Pellets as large as 2 x 2-1/2 inches were manufactured. It was also shown that PB-RDX powder can be pressed by this technique.

Von Neuman, John, "Theory of Detonation Waves Progress Report", Institute for Advanced Study, Princeton, New Jersey, Division B National Defense Research Office of the Office of Scientific Research and Development 57-7-17-2 (2) (May 4, 1942); AD 159123. A-1-1-17

This report presents the results of an investigation of the mechanism by which a stationary detonation wave maintains itself and progresses through the explosive.

Support was found for the hypothesis that the detonation wave initiates the detonation in the neighboring layer of the intact explosive by the discontinuity of material velocity which it produces. It is believed that the discontinuity of material velocity acts like a vehement mechanical blow (1,500 meters per second) and is more effective than high temperature.

Pack, D. C., and Evans, W. M., "Penetration by High-Velocity ("Munroe") Jets, I.", Proceedings of the Physical Society of London, Series B, 64 (4), 298-302 (April, 1951). A-1-1-18

The two stages of penetration were separated experimentally. The large penetrations measured in lead targets are shown to result from the flow which takes place in the metal after the jet itself has been consumed. For a given jet at a given stand-off it is possible to predict the penetration into a combination of targets from the results of a very small number of standard experiments. The method depends upon the calculation of a certain quantity which is constant for a given jet at a given stand-off, and examples are given of the determination of this quantity from experimental data. (Physics Abstracts, 1951).

Parlin, Ransom B., and Giddings, Calvin J., "The Application of Probability Theory to Explosive-Ignition Phenomena", Technical Report No. 17, Institute for the Study of Rate Processes, University of Utah (September 30, 1955), Contract N7onr-45103; AD 75643. A-1-1-19

The problem of explosive ignition concerns itself both with probability of occurrence of local-energy fluctuations and with the transition of these disturbances into a combustion or detonation wave. The former concept does not appear to have been comprehensively discussed; a treatment of this process is presented here. The theory is applied to several cases of impact ignition, both with and without grit particles and it is found to be in good agreement with experiment. Information is obtained through application of the theory concerning the nature and location of the local disturbances responsible for ignition.

Roth, Julius, "The Forming of Metals by Explosives", Explosives Engineer, 37 (2), 52-55 (March-April, 1959). A-1-1-20

The explosive parameters which are important in metal forming are maximum pressure developed, available energy, and velocity of propagation. The detonation pressure is not readily amenable to measurement and is usually calculated from hydrodynamic theory of detonation. Explosive parameters for RDX, PETN, Pentolite, and TNT are given for detonation velocity, energy, and maximum pressure. Scaling laws for pressure decay under water are given on the basis of computations by Cole.

Scardin, H., "Measurements of Spherical Shock Waves", Communications on Pure and Applied Mathematics, 7 (1), 223-243 (1954). A-1-1-21

Although this article is primarily concerned with shock waves produced by explosives in air, it develops pressure-versus-time data for various explosives. Experimental data are shown which verify the experimental results. Photographs are shown from multiple-spark camera, streak camera, condenser-microphone, Kerr-cell photography, and X-ray photography.

Taylor, J., Detonation in Condensed Explosives, Oxford Press, Fairlong (1952). A-1-1-22

The book deals with the physical and chemical changes which take place during an explosion. The mechanism of detonation of commercial explosives is discussed and a brief description of the propagation of detonation in condensed explosives is given. The system for calculation of the numerical values of the detonation parameters is shown. The thermochemistry of explosives and the hydrodynamic theory of detonation are discussed.

Aerex Liquid Explosive, Aerojet General Corporation, Azusa, California. A-1-1-23

The explosive is shipped as two separate liquids neither of which needs to be handled as an explosive. When mixed in the proper ratio, the two liquids become an explosive mixture. The mixture can be detonated with a No. 8 electric cap. The

detonation velocity is 20,000 to 22,000 fps. The pressure characteristics are similar to C-4 composition explosive. It may be used under water in either a polyethylene bag or a glass flask. It costs approximately one dollar per pound in lots of 5 to 10 gallons. It weighs 9-1/2 pounds per gallon. By mixing ammonium nitrates with the liquid, an explosive with a power equivalent to 60 per cent gelatin dynamite is obtained in solid form.

Du Pont EL-506 Flexible Sheet Explosive, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware. A-1-1-24

The sheet explosive is a PETN base and is obtainable in thickness from 0.084 to 0.328 inch. The density of loading varies from 2.0 to 8.0 grams/inch squared. The explosive is flexible, easy to cut with a knife, and easy to shape. It has a detonation velocity of 6500 to 7500 meters per second. Some of the specific applications of this explosive to the cutting and hardening of metals are given.

Du Pont Line-Wave Generators, Bulletin No. ES-58-2, E. I. du Pont de Nemours, Incorporated, Wilmington, Delaware. A-1-1-25

The generators are in the form of perforated equilateral triangles measuring 10.9 inches on a side and are prepared from flexible Du Pont Sheet explosive. Two thicknesses (0.050 and 0.168 inch) of explosive are presently available.

The rate of detonation of the 0.168-inch-thick generator is approximately 7200 meters per second from apex to apex and 6200 meters per second from an apex to the midpoint of the opposite side. The 0.050-inch-thick generator has a rate of detonation of 6800 meters per second from apex to apex and 5800 meters per second from an apex to the midpoint of the opposite side.

Du Pont Mild Detonating Fuze (MDF), Bulletin No. ES-58-3B, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware. A-1-1-26

This bulletin contains information concerning the general characteristics of MDF and the various forms and accessories available. Loadings down to 4 grains per foot are available.

Du Pont Flexible Linear Shaped Charge, Bulletin No. ES-61-1A, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware. A-1-1-27

The Du Pont Flexible Linear Shaped Charge (FLSC) consists of a V-shaped, flexible metal tube containing a high explosive core. When detonated it provides a sharply-defined cutting action. Presently available with cores of either RDX or PETN in a sheath of lead (the use of other metal coverings is being investigated), FLSC possesses a high degree of flexibility and can be used in a variety of cutting and separating applications. It can be initiated with standard blasting caps or with initiators designed specifically for this application.

Blasters' Handbook, Fourteenth Edition, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware. A-1-1-28

This book provides a comprehensive discussion of explosives; procedures in handling and proper applications. The procedures described in this handbook are preferred practices. There is no direct mention of explosive forming; however, it is an excellent reference for any operation which requires the handling of explosives.

Shaped Charge Brochure, Thiokol Chemical Corporation, Hunter-Bristol Division, Bristol, Pennsylvania (December, 1959). A-1-1-29

This brochure outlines some of the problems currently being solved by the use of shaped charges. A discussion of techniques is presented to assist the design engineer in the evaluation of applicability of shaped charges to specific metal cutting or forming problems.

Graphs are given for the design of shaped charges for various material thicknesses.

"Fundamental Research on High Explosives", Final Summary Report No. C-58247, Arthur D. Little, Inc., Cambridge, Massachusetts, Contract No. DA-19-020-ORD-47, Project TA 3-5001 (Continuation of Contract No. DA-19-020-ORD-12) (May 31, 1954); AD 32262. A-1-1-30

The history of the investigation is given with a summary of the important conclusions reached. Interim reports containing the details of the experimental data are listed together with publications resulting from these studies. A list of errors and corrections is given for Study of Pure Explosive Compounds. (See also AD 21289, AD 29631, and AD 34350.)

"Explosives and Demolitions", FM 5-25, Department of the Army (September, 1954). A-1-1-31

The various explosives available to the United States field forces and their proper use, handling, storage, and transport are discussed. The equipment and the accessories used in the field are described and their separate functions are explained. Preparation, calculation, and the placement and firing of charges for demolition are described and illustrated. Appropriate formulas and their uses are given. Methods are outlined for the demolition of structures built of timber, steel, and concrete. Means of destruction of bridges, equipment, supplies, buildings, and communication systems are also described.

"ONR Symposium on Detonation", February 9-10, 1955, Vol 2, Naval Ordnance Laboratory, White Oak, Maryland (1955). A-1-1-32

Papers are presented that deal with the following topics: charge preparation for precise detonation velocity studies; a microwave technique for measuring detonation

velocity; measurement of detonation temperatures; a new cine microscope and its application to detonation phenomena; the measurement of density changes in gaseous detonations; the attainment of thermodynamic equilibrium in detonation waves; the structure of a detonation front; high-temperature thermodynamics and gaseous detonations in mixtures of cyanogen, oxygen, and nitrogen; detonation in gases at low pressure; measurements on gaseous detonation waves; studies on gaseous detonation; condensation shocks and weak detonation; the structure of a steady-state plane detonation wave with finite reaction rate; the measurement of Chapman-Jouguent pressure for explosives; measurement of the Chapman-Jouguent pressure and reaction-zone length in a detonating high explosive; the detonation zone in condensed explosives; calculation of the detonation properties of solid explosives with the Kistiakowsky-Wilson equation of state; a solid-state model for detonations; diameter effect in condensed explosives; the detonation behavior of liquid TNT; detonation in homogeneous explosives; particle size effects in one and two-component explosives; detonation wave fronts in ideal and nonideal detonation; determination of reaction rate of sodium nitrate and the equation of state of 50/50 TNT-$NaNO_3$; the decomposition of alpha-lead oxide; the detonation of oxides; origin of luminosity in detonation flames; the role of gas pockets in the propagation of low-velocity detonation; sensitiveness to detonation; and initiation of military explosives by projectile impact.

"Flexible Sheet-Explosive for Metal Cutting", Welding Engineer, 44 (6), 46-47 (June, 1959). A-1-1-33

Du Pont EL-506A, a sheet explosive, is used for the cutting of metals. Advantages of this explosive are: (1) maximum cutting action with minimum weight of explosive, (2) easy application, (3) safety in storage, handling, and application, (4) increased reliability, and (5) maximum uniformity of sheet-explosive formation. Explosive sheet is cut to the desired size, adhesively bonded to the surface of the workpiece, and detonated by an electric primer cap.

"Explosive Forming", Electronics, 31 (42), 24-25 (October 17, 1958). A-1-1-34

The experimental work in explosive forming being conducted at Convair is discussed. Several examples of the type of parts which can be formed by this process are given. Their process is called Dynaforming and requires either chemical explosives or electrical discharge.

"Hydromex: Research and Development Payoff with a Bang", Canadian Chemical Processing, 44 (70-71), 146, 149 (June, 1960). A-1-1-35

This article describes a new explosive, Hydromex, which has been developed in Canada. It is a slurry composed of ammonium nitrate, TNT pellets, and 10 per cent-20 per cent water. The velocities of detonation are in the same range as high-strength nitroglycerine explosives, but Hydromex is very safe to handle and requires a Pentolite pellet to detonate it. Details of the mechanism of its detonation are given.

Brink, David E., Hurst, Roy F., and Kells, Milton C., "Plane Wave Generators", Technical Report No. 021-58, Stanford Research Institute, Menlo Park, California (March 14, 1958); AD 232666. A-1-1-36

Techniques were devised for producing detonation fronts that are planar over areas significant for experimental work. Several techniques are described for producing plane waves and for the selection of the method most likely to satisfy the requirements of a given problem. Line generators are necessarily discussed as part of a plane-wave technique.

Ostroskii, A. P., Deep-Hole Drilling with Explosives, Gostoptekhizdat, State Scientific and Technical Publishing House, Petroleum and Mineral-Fuel Industry, Moscow (1960). In Russian with a translation by Consultants Bureau, New York. A-1-1-37

This book discusses the new trend in worldwide application of explosives in technology. It presents considerable experimental material on the effect of explosions in solid media; material that is not only interesting to specialists in mining but also to physicists.

Many phenomena associated with the shattering effect of explosions on solid media still await explanation. The fact that these phenomena have been already subjected to experimental study undoubtedly adds to the knowledge of one of the most meagerly investigated areas of the science of explosions.

Cross References.

| | |
|---|---|
| B-1-4 | Peak pressures were measured for charges of H-6, Comp B, DYX, and DX. |
| B-1-6 | Gives peak pressure and impulse from an air blast of Terrier missile warheads with two different explosives. |
| F-1-0-55 | Discusses liquid explosive, Aerex, used by Aerojet. |
| G-1-1-16 | Discusses application of sheet explosive for impact hardening. |
| J-2-6 | Describes shaped charges and gives a system for detonating them. |

## Chemical

### Low Explosives. A-1-2

Dickinson, Thomas A., "The Use of Explosive Charges for Forming Sheet Metal", Sheet Metal Industries, 35 (371), 213-215 (March, 1958). A-1-2-1

This article reports on experimental work being performed in the U. S. It indicates that Winchester Western Division of Olin Mathieson Chemical Corporation

stimulated much present interest by using blank cartridges to form metal-flashlight components. Mathieson's use of "shaped charges" to vary pressure-time patterns is discussed. The article explains briefly direct forming with cartridge gases, cartridge acceleration of hammer forging, compression of hydraulic fluid with cartridge gases, and cupping and drawing. An outline of present problems is given which cites the general lack of knowledge of effects of various charges on different metallic grain structures. It is predicted that limitations of the process will soon be determined.

Ebert, K. A., Hofmann, W., and Seitz, G., "Some Observations on Shooting Bolts into Metals", Zeit. Für Metallkunde, 47 (1), 24-28 (January, 1956). In German. A-1-2-2

Observations on driving bolts into metals, the driving of steel bolts by powder charges into aluminum, copper, and steel, and forces necessary for extracting bolts are discussed.

Gardner, Annesta R., "Explosives: Portable Power Packs", Product Engineering, 29 (1), 56 (January 6, 1958). A-1-2-3

This article covers various uses of explosives, such as in power actuated stud-driving, forming metals, and cartridge-activated tube cutting.

Lord, C. B., "Gunpowder Deserts Mars for Vulcan", American Machinist, 72 (1), 254-258 (February 6, 1930). A-1-2-4

This article describes the Temple gun, an explosive stud driver. This gun will drive a 1/2-inch stud bolt into a 7/16-inch hole without stripping threads or burring the hole. Many applications are discussed.

Pallingston, Arnold O., and Weinstein, Murray, "Method of Calculation of Interior Ballistic Properties of Propellants from Closed Bomb Data", Technical Report No. 2005, Project No. TA1-5006B, Item G (June, 1954); AD 39667. A-1-2-5

The closed-bomb calculation technique is discussed for use in the calculation of relative force, relative quickness, and linear burning rate for artillery propellants. The apparatus consists of a closed bomb, a piezoelectric gage, a Dumont type 235 oscilloscope, associated electrical apparatus, and a recording camera. Propellant samples to be investigated are placed in the closed bomb and fired. The pressure and dp/dt are characterized by the amount of charge produced by the piezoelectric pressure gage. The charge built up by the gage is fitted into the oscilloscope and recorded by the camera. The methods described are essentially for use with experimental propellants and are not intended for production or quality control. The report contains 36 pages of illustration.

<u>Du Pont Pyrocore Igniter for Propellants</u>, Bulletin No. ES-57-2c, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware. A-1-2-6

The general characteristics of materials used for the ignition of propellants are given. Some information on special electric initiators for the igniter materials is also included.

"Packaged Power", Olin Mathieson Chemical Corporation, Ramset Winchester-Western Division, East Alton, Illinois (1961). A-1-2-7

This brochure explains the applications of power cartridges to the potential user. It describes the basic ballistic behavior of cartridge-actuated systems.

"Metal Forming Using Power Cartridges", Olin Mathieson Chemical Corporation, Ramset Winchester-Western Division, East Alton, Illinois (January 16, 1957). A-1-2-8

This report is on progress in metal forming with cartridges.

"Shooting for Strange New Targets", Business Week, 135-136 (October 27, 1956). A-1-2-9

This is a staff article which describes work being done with packaged power, tells who is doing it, and indicates possible uses.

McDonald, R. J., and Schwope, A. D., "Explosively Driven Stud Having Polished Point", U. S. Patent No. 2,751,808 (June 26, 1956). A-1-2-10

An explosive charge is detonated which drives the stud into the desired material. The polished point adds to the holding power of the stud.

Chatten, V. H., "Apparatus for Metal Forming Using Explosive Pressures", U. S. Patent No. 2,935,038 (May 3, 1960). A-1-2-11

The invention consists of an enclosed chamber where an explosive is detonated. The explosion initiates a pressure wave in this chamber which forces metal into a die set in the bottom.

<u>Cross References.</u>

A-1-1-9 Information on chemistry, history of development, and methods of manufacture of low power explosives.

C-3-1 Discusses advantages and disadvantages of various propulsion systems.

F-1-0-63 Discusses experimental propellant driven press.

F-1-7-7 Modern application of gunpowder as "explosive tools" for shock forming.

F-1-0-76 Study of Convair's early work using low explosives.

## Chemical

### Detonators. A-1-3

Nightingale, H., "Hazards Connected with Electrical Blasting Caps on Similar Types of Initiators Owing to Radio Frequency Radiations", Memorandum Report No. MR-27, Picatinny Arsenal, Dover, New Jersey (December, 1952); AD 15793. A-1-3-1

An investigation was made to determine the handling procedures for electrical detonators – blasting caps, electric squibs, bridge-type detonators, and conductive mix detonators. Rules for handling the detonators were devised on the basis of electrical-initiator characteristics and RF-radiation conditions. The types of metallic ammunition in which initiators are inserted are believed to act as a complete RF shield on the outside. The investigation established that safe conditions can be achieved by using leads of a length which are not resonant to local transmission frequencies and by twisting and keeping the leads close to ground. Precautions should be taken against resistance-type welding or RF heating near an initiator. A table is included which indicates desirable minimum distances of separation between radio-broadcasting transmitters and electrical-initiator operation. The report has 16 pages of illustration.

Taylor, Guy B., and Cope, W. C., "Initial Priming Substances for High Explosives", Technical Paper No. 162, United States Bureau of Mines (November, 1917). A-1-3-2

This paper discusses the development of new priming mixtures for blasting caps which are more efficient than mercury-fulminate mixtures. The theory of selection of new priming mixtures as well as the test results of experimental findings are presented.

Wood, R. W., "Optical and Physical Effects of High Explosives", Proceedings Royal Society, London, Series A, 157 (891), 249-261 (1936). A-1-3-3

The deformation of the copper cap on an explosive detonator is studied to gain information about the mechanism of detonation. A spectroscopic investigation of exploding materials is also made.

General Discussion Librascope Exploding Bridgewire Ordnance System, Librascope Division of General Precision, Inc., Sunnyvale, California. A-1-3-4

A discussion of the basic technical understanding of the exploding-bridgewire phenomenon and the application of this concept to missile- and spacecraft-ordnance

systems is presented. Although the use of this type of device is too expensive for consideration with commercial-blasting operations, the inherent safety of the system will make it usable for elimination of hazards of RF when the price becomes more competitive with the standard blasting cap.

LaHaye, Frank, "Accidental Firing of Electro-Explosive Ordnance", Missile Design and Development, 6 (12), 28-30, 58 (December, 1959). A-1-3-5

The possibility of accidental firing of military type electrically initiated ordnance by stray current or RF energy is explored. Recommendations are given for minimizing the potential hazards by the inclusion of danger signals which can be recognized.

"Radio Hazard in the Use and Transportation of Electric Blasting Caps", Technical Service Bulletin No. 24, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware (December 5, 1956). A-1-3-6

This bulletin contains the latest issue of "Radio Frequency Energy A Potential Hazard in the Use and Transportation of Electric Blasting Caps" by the Institute of Makers of Explosives, Pamphlet No. 20. The information applies only to commercial U. S. blasting caps and not to military or foreign caps which may fire at considerably less current.

"Rules for Storing, Transporting, and Shipping Explosives", Pamphlet No. 5, Institute of Makers of Explosives, New York (1956). A-1-3-7

This pamphlet contains safety rules to guard against accidents in storing, transporting, and shipping explosives.

## Chemical

### Gas Combustion. A-1-4

Kruse, Philip, and Miller, John, "Explosive Forming with Combustible Gas Mixtures", Metals Progress, 80 (2), 76-78 (August, 1961). A-1-4-1

This article describes one of the newest entries into the high-energy-rate metalworking field. Mixtures of hydrogen, oxygen, and an inert gas are used as the energy source in a closed-die system to form parts. The forming pressures can be controlled more accurately and the combustible gas is, in effect, an ideally shaped charge since it is always in contact with the workpiece. The process, however, still has some inherent disadvantages consisting of the requirements for heavier tooling to contain the explosive force and longer times for loading and unloading the parts from the die. The size of parts which can be produced by this technique is limited.

Lingen, Richard E., and Cruver, Ralph W., "Explosive Forming with Gas Mixtures", ASTME Report No. SP 62-02, presented at the Creative Manufacturing Seminars (1961-1962). A-1-4-2

This paper is a collection of data gathered from experience in explosive forming with gas mixtures at the Boeing Company. Background information resulting from a literature survey is included. This technique has an advantage over chemical explosive forming in that a gas mixture assumes the shape of the container and, therefore, becomes an optimum shaped charge regardless of quantity. The charge is in intimate contact with the workpiece which removes the variable of stand-off distance. In addition, gas mixtures eliminate the usual water pit, and thus provide a more rapid operation. On the other hand, tooling must be more expensive since a closed system which will withstand the contained pressure is necessary for the operation.

"Experimental Gas Cell Powers Metal-Forming Explosions", Machine Design, 32 (15), 8 (July 21, 1960). A-1-4-3

This article covers work being done at Battelle Memorial Institute by Dr. John McCallum on using a generated gas for fuel in an explosive-forming operation. The gas is generated by an electrolytic cell consisting of nickel-plated steel electrodes immersed in a weak caustic solution. The advantage in using gas explosions is that the force is smaller and the duration greater, and so there is more control of the system.

"Gas Generator Cuts Metal Shaping Costs", Chemical and Engineering News, 38 (24), 60-62 (June 13, 1960). A-1-4-4

A new electrolytic gas generator developed by Dr. John McCallum of Battelle Memorial Institute turns out hydrogen and oxygen in stoichiometric mixture from water. This device has applications for less expensive shaping of large metal sections. When the gases explode to create pressures 10 times greater than the starting pressure within milliseconds the force generated can be safely directed to shape parts, provided a closed system is used. The shock wave from the exploding gas mixtures has a lower velocity than high explosives and is believed to be more applicable to the forming of thin metal parts.

## Energy Sources

Electrical A-2-0

Courtis, W. F., "Electrical Discharge Metal Forming", Paper No. 62-MD-23, American Society of Mechanical Engineers (February 2, 1962). A-2-0-1

The subject of electrical discharge metal forming is discussed with a brief description of the circuitry employed and an analysis of the reactions involved. The advantages and limitations of this form of high-energy-rate method are indicated as well as the types of metal and configurations which are suitable for this process. The direction of planned future development effort and the hoped-for results are stated.

Derian, Arthur R., "Direct Conversion of Electrical Energy into Work, Electro-Hydraulic Forming", ASTME Report No. SP 60-163, presented at the Creative Manufacturing Seminars (1960-1961). A-2-0-2

A general discussion of "electro-hydraulic forming" is presented in this paper. A typical cycle for such a unit consists of (1) a capacitor or bank of capacitors is charged to a high potential, (2) this energy is discharged under controlled conditions across a gap established by electrodes immersed in a suitable medium, (3) the high-energy waves that are created by the sudden discharge propagate at high velocities radially outward from the arc, and (4) finally, these high-energy waves, by supplying the necessary forces, stress the materials beyond their elastic limit and form the work material into desired shapes and sizes.

Feddersen, E. W., "Electro-Hydraulic Process of High Energy Rate Forming", ASTME Report No. SP 60-164, presented at the Creative Manufacturing Seminars (1960-1961). A-2-0-3

This paper presents the work which was conducted at Convair on the electro-hydraulic process; its development as a production tool, its applications, and the tooling developed during the past several years. The major applications are in the forming of tube type details, although some work has been accomplished on flat plate. Applications in close-tolerance sizing of tubing has also been demonstrated.

Felts, Robert, "Application of the Electrohydraulic Effect to Metal Forming", ASTME Report No. SP 62-08, presented at the Creative Manufacturing Seminars (1961-1962). A-2-0-4

This paper describes the electrohydraulic effect and discusses its application to the forming of metals. The rate of application of the shock wave from the direct conversion of electrical energy is greater at source than for an explosive charge. The use of this system is very similar to the explosive-forming technique. A discussion of the work which has been accomplished with this technique and parts which have been made are presented.

Herchenroeder, L. W., "Electrohydraulic Forming", Aircraft Production, 22 (8), 302-303 (August, 1960). A-2-0-5

A general discussion of the fundamentals of electric-discharge-forming devices is given. It was found that the internal inductance of capacitors is one of the factors that affects the rate of rise of current in the discharge-circuit. The discharge-circuit is a series RLC circuit.

Judge, J., "Explosive Forming: No Panacea Seen", Missile and Rockets, 6 (17), 37-39 (April 25, 1960). A-2-0-6

Convair's viewpoint of the high-energy-rate forming field is presented. It is believed that explosive forming does not lend itself to large-volume production and requires extreme safety measures. The hydro-electric method is accurate, repeatable, and can be used within an inhabited factory because of the complete controllability. The pneumatic-mechanical method is semiconventional, using simple punches and complicated dies in some instances. Some of the early work with the electro-spark device utilized voltages from 14,000 to 22,000 volts and from 30 to 60 microfarads. Power increases were realized by reducing the voltage to 4000 and increasing the capacity to 1200 microfarads. The use of the exploding-bridge wire system was also found to be advantageous.

Wagner, H. J., and Dunleavy, J. G., "Hydrospark Forming – Evolution of the Process", The Tool Engineer, 44 (3), 83-86 (March, 1960). A-2-0-7

This article traces the development of hydrospark forming and discusses the applications. It was found that the energy release was comparable to that obtainable with high explosives.

Wagner, H. J., and Boulger, F. W., "High-Velocity Metalworking Processes Based on the Sudden Release of Electrical Energy", DMIC Memorandum 70 (October 27, 1960). A-2-0-8

This report presents various high-energy metalworking processes in which the energy applied to the workpiece originates as electrical energy stored in a bank of high-voltage capacitors. In several methods a high-amplitude, short-duration current pulse is used to create an underwater shock wave, either by causing a spark to jump across a submerged spark gap or by literally exploding a submerged filament wire in the vicinity of the workpiece. In another method the current pulse produces a rapidly charging magnetic field in a coil. The various processes are discussed showing the capabilities and limitations. Calculations are also presented for determining the working capacity of such equipment.

"Tough Metals Shaped by Electrical Explosion", Engineering, 191 (4559), 645 (May 5, 1961). A-2-0-9

A general review of the work being conducted at G. E. on capacitor-discharge electro-spark forming is given. No new information is presented on capabilities or techniques of operation.

"Spark Bomb: A New Metal Former – Can Instant Power Handle the Tough Shaping Jobs?", The Iron Age, 184 (12), 109 (September 17, 1959). A-2-0-10

A general discussion of electric-discharge equipment is given. Future applications and limitations of the equipment are discussed.

"Explosive Forming", Tool Engineer, 45 (1), 141-142 (July, 1960). A-2-0-11

This short article gives advantages of using high-energy-rate forming and discusses the types of workpieces best suited to this method.

Kegg, Richard L., "Effects of Process Variables in Electric Discharge Forming", Paper presented at the Twelfth General Assembly of CIRP, The Hague, September 8-15, 1962, Technical Center for Metalworking, Metal Institute (TNO), Delft, Holland. A-2-0-12

The two processes of electric-discharge forming (edf) of metals, which are underwater-spark forming (esf) and electromagnetic forming (emf), are described and their position in the field of metal forming is outlined. A technique is presented to determine the magnitude of the strain rate in these processes. Bulging a two-inch 52.8-millimeter-diameter tube produced a strain rate in the order of 3,000 inches per inch per second. To find experimentally the effects of major process variables, a clamp-sheet metal diaphragm was exposed in one case to a shock wave and in the other to a transient magnetic field. In esf the deformation of the diaphragm increased with increasing stored energy, die diameter, distance from spark to surface of water, spark gap, and inverse of sheet thickness. It decreased with increasing distance from spark to workpiece and diameter of initiating wire. In emf the influence of variables is somewhat similar. The deformation of the diaphragm increased with increasing stored electrical energy and it decreased with increasing distance from magnetic coil to workpiece, spacing of magnetic coil turns, and added inductance.

Cross References.

A-1-0-1 Discusses safety of electrical high-energy equipment operation.

A-1-0-2 General coverage of electrical high-energy-rate sources, and comparison with conventional forming equipment.

A-1-0-3 Reviews past accomplishments and points out areas where information is lacking in electrical high-energy-rate methods.

A-1-0-4 Describes electrical high-energy forming and compares it with conventional forming.

A-1-0-5 Gives limitations and applications of electrical high-energy forming and the response of several metals to this method.

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| A-1-0-6 | A nontechnical report which covers "hydroelectric" forming. |
| A-1-1-3 | Compares energy output of electrical high-energy sources with that of other high-energy sources. Also gives unusual characteristics of the electrical high-energy system. |
| A-2-1-1 | Concerns electric-discharge forming of components. |
| A-2-3-6 | Shows design of a special switch called magnetohydrodynamic switch. |
| A-3-0-1 | Discusses all forms of high-energy-rate forming methods including high-mass systems, high-velocity systems, and high-temperature systems. |
| F-1-1-14 | Discusses electrohydraulic forming and electrical energy sources. |

## Electrical

### Spark. A-2-1

Early, H. C., "High Speed Printing and Perforating Machine", U. S. Patent No. 2,737,882 (March 13, 1956). A-2-1-1

Claims 20 through 27 deal with the electrodischarge forming of components. Claim 20 describes a method of making a "predetermined formation in a formable member comprising the steps of producing an electrical discharge to heat and expand gases exposed to the discharge, placing a member to be formed adjacent said discharge, confining the gases to apply the force of the heated and expanded gases resulting from the electrical discharge to the member, and restraining displacement of that portion of the member that surrounds an area having an outline corresponding to the outline of the formation desired and which is subjected to the force from the electrical discharge to a greater extent than the portion of the member confined within the outline of the formation desired."

Claim 21 describes a method of making "predetermined formations in a formable member which comprises producing through a volume of fluid confined closely adjacent one face of the formable member, an electrical jump spark to create, by heating expansion of said fluid by said spark an explosive increase of pressure of said fluid against said formable member to thereby drive said formable member with forming force against a forming member."

Edmonson, R. B., Olsen, H. L., and Gayhart, E. L., "Application of Ideal Gas Theory to the Gaseous Expansion from an Electric Spark", Journal of Applied Physics, 25 (8), 1008-1013 (August, 1954). A-2-1-2

The gaseous expansion from an electric spark is described in this paper in terms of ideal gas theory. The assumption is made that a quantity of energy is injected into a small gas volume in an infinitesimally short time and that the initial volume of gas then expands until it reaches the pre-spark pressure at an elevated temperature. Experimental results are given for a condenser discharge illustrating the dependence of the

pressure-equilibrated-gas volume upon initial pressure and condenser energy. These results are interpreted using the ideal-gas model presented. The significance of this expansion to the problem of spark ignition in combustible gases is discussed.

Kegg, Richard L., and Kalpakcioglue, Serope, "Research in Electric Discharge Forming of Metals", ASTME Report No. SP 62-78, presented at the Creative Manufacturing Seminars (1961-1962). A-2-1-3

The process of underwater-electric-discharge forming of metals is described. A technique is presented to determine the magnitude of the strain rate in this process. In bulging a 2 in. diameter tube, the strain rate was found to be of the order of 3000 inches per inch per second. The sheet-metal diaphragm blast gauge was used in an experimental program to determine the effects of major process variables on the amount of forming obtained in underwater-electric-discharge forming. The gauge deflection increased with increasing energy, distance from spark to surface of water, spark gap, die radius, and inverse of sheet thickness. It decreased with increasing stand off and diameter of initiating wire.

LeGrand, Rupert, "Underwater 'Lightning' Sparks New Metal Forming Process", American Machinist, 103 (22), 123-124 (October 19, 1959). A-2-1-4

High-energy-spark discharge forms sheet-metal parts in 40-millionths of a second. The process is safe, predictable, and capable of use in the shop.

Martin, Edward A., "Experimental Investigation of a High-Energy Density, High-Pressure Arc Plasma", Journal of Applied Physics, 31 (2), 255-267 (February, 1960). A-2-1-5

The underwater spark is utilized to study the fundamental parameters of a plasma at 30,000 K and 10,000 atmospheres pressure. The 25-kv spark, obtained by underwater discharge of capacitors, has a stored energy of 1800 joules, the inertia of the water providing the confinement necessary to develop high pressures. Phenomena relating to the initiating wire (exploded wire) are discussed. Kerr cell photographs show that spherical structures are formed around both electrodes under certain conditions. A possible explanation is postulated. A detailed energy balance and particle balance are carried out. The results show that the plasma has great capability to store energy in dissociation, excitation, and ionization without a corresponding increase in temperature. The plasma is 30 per cent ionized and the total particle density is about $2 \times 10^{27}$ per cubic meter. At this density the plasma radiates a blackbody spectrum. Pressures are obtained by calculation based on the rate of spark-channel expansion and the shock properties of the water. The plasma is found to have an internal pressure of the same order of magnitude as the external pressure because of inter-particle Coulomb forces. Plasma conductivity calculated from equations of Gvosdover and Spitzer and Harm agree very well with the experimental value. The study is basically experimental, with the emphasis in interpretation being placed on reliability of the conclusions rather than on refined accuracy.

Martin, Edward A., "The Underwater Spark: An Example of Gaseous Conduction at about 10,000 Atmospheres", Report No. 2048-12-F, The University of Michigan, Contract No. DA-20-018-ORD-12242, ORD Project No. TB 3-001(317) (July, 1956); AD 105473. A-2-1-6

The underwater spark is treated as a problem in gaseous electrical conduction at pressures of the order of 10,000 atmospheres. Four basic spark parameters are determined as functions of time. The channel-size quantities permit carrying out a particle balance and an energy balance as functions of time. The mutually consistent results provide an extension of the theory of gaseous conduction into the domain of extremely high pressures. The research work was carried out with a 5.8 microfarad capacitor charged to 25 kilovolts. A peak current of 85,000 amperes was found.

Schrom, E. C., "Metal Forming with Capacitor Discharge Electro-Spark", ASTME Report, presented at the Creative Manufacturing Seminars (1961-1962). A-2-1-7

This paper covers the experimental equipment and some of the work conducted at the General Electric Company General Engineering Laboratory. Their equipment is rated at 20 kv, 187.5 mfd and is capable of storing 37,500 joules of electric energy. The ringing frequency of 12.5 kc, and a total circuit inductance of 1.6 microhenries was found. Some of the empirical test results are correlated with the theoretical-energy calculations. The efficiency of the system was investigated on the basis of cup-forming tests. The following materials were investigated: copper, columbium, Type 302 and 410 stainless steel, phosphor bronze, and A55 titanium.

"Explosive Forming", Aircraft Production, 22 (1), 39 (January, 1960). A-2-1-8

Some of the experimental work being conducted at Republic Aviation on electric-spark forming is discussed.

"'Packaged Lightning' Dynamite's Successor in High-Energy Forming?", American Machinist/Metalworking Manufacturing, 104 (8), 104-105 (April 18, 1960). A-2-1-9

Convair's electric discharge device with the trade name Hi-Vo-Pac is described. The unit consists of a portable metal box containing capacitors, switching circuits, a power-regulating variac, charging switch, and manual- or automatic-discharge switches. The energy stored in the unit is equal to 10,800 foot-pounds. Dies for the unit are completely closed for increased efficiency of operation. The charging rate on the equipment is six seconds.

"Spark Bomb Method Promises In-Plant Explosive Forming", Space Aeronautics, 33 (2), 99-101 (February, 1960). A-2-1-10

This article covers spark-gap forming at Republic Aviation. The process is still in the research phase but shows promise. The electric energy is stored in high-voltage capacitors and then released in forty millionths of a second across a gap between

electrodes submerged in water inside a die. Four and one-half-inch diameter parts have been formed from a variety of materials. In the research model, 1800 joules was available and charging time was 1/2 minute. A production machine is now being designed.

"Spark Forming Takes Its Place on the Line", Steel, 149 (20), 172-73 (November 13, 1961). A-2-1-11

The use of spark forming at Convair, Fort Worth, is described in this article. The forming of tubing is performed in split dies and a water medium is used for shock-wave transmission. The total energy output may be maintained at a low level since it operates in a closed system.

"Electro-Spark Forming", Industrial and Engineering Chemistry, 53 (1), Supplementary 27A-28A (May, 1961). A-2-1-12

This article discusses General Electric's development of "capacitor discharge electro-spark" energy source used in forming metals. Their tests were conducted under water and with an evacuated die. A 35,000 volt discharge was used and pieces up to 10 inches in diameter and 1/4 inch thick were formed.

Redstreake, W. M., "Now Non-Chemical Explosions Shape Hard-to-Form Metal", Iron Age, 188 (17), 88-89 (October 26, 1961). A-2-1-13

This article describes work being done at Electro-Hydraulics, Incorporated, in the field of forming with electrical-discharge energy. The process basically is the sudden release of electrical energy which produces a shock wave in the fluid medium. These waves in turn press against the metal blank and force it into the die.

Early, H. C., and Orr, L. W., "High Speed Printing and Perforating Machine", U. S. Patent No. 2,737,882 (March 13, 1956). A-2-1-14

This device utilizes energy from a spark discharge to produce physical indentations on some means of record. Its object is to print, as rapidly as possible, material to be used in conjunction with high-speed computers. The discharge generates a force which pushes an anvil against the tape and prints the desired letter.

"Electrohydraulic Forming", Machinery, 100, 1347-1349 (June 13, 1962). A-2-1-15

The article discusses electrohydraulic forming which has recently been used in England. A detailed description of this electrohydraulic forming system is given. The work was done with equipment ranging in capacity up to 20,000 volts.

Cross References.

A-1-1-15 General outline of work done in electrohydraulic forming.

A-1-1-34 Experimental work at Convair in electrical discharge forming is described.

A-2-2-1 Discusses use of spark-gap transducer to produce shock waves in a liquid medium.

A-2-3-3 General discussion of electrospark forming is given.

F-2-1-1 Describes energy-transfer phenomena in electrohydraulic metal forming.

F-2-7-2 Describes work being done in electrospark forming at General Electric, Chrysler, Convair, and Republic Aviation.

F-3-0-12 Reviews development of an electrical discharge unit (Hi-Vo-Pak).

## Electrical

### Wire. A-2-2

Cadwell, G. C., "Spark Forming Goes to Work", American Machinist/Metalworking Manufacturing, 105 (23), 126-129 (November 13, 1961). A-2-2-1

The use of two different electrical-discharge-forming processes employed at Rohr Aircraft are discussed. They have successfully produced hundreds of parts from difficult-to-form materials. Both machines can form parts either by using a spark-gap transducer to produce shock waves in water, oil, or some other liquid medium or by vaporizing wire which is connected across a spark gap.

Chace, William G., "A Bibliography of the Electrically Exploded Wire Phenomenon", ORD Research Notes No. 2, Air Force Cambridge Research Center, Bedford, Massachusetts (November, 1958); AD 152640. A-2-2-2

A bibliography of all literature on the electrically exploded-wire phenomenon published to the year 1958. A few of the articles are covered with abstracts.

Conn, William M., "Studien zum Mechanisms von elektrischen Drahtexplosionen" ("Studies on the Mechanism of Electrical Wire Explosions"), Zeitschrift fur Angewandte Physik, 7 (11), 539-554 (1955). No translation available. A-2-2-3

This article contains information on exploding-wire characteristics. It covers the past work published on the subject and experimental work conducted by the author. Numerous references are given as well as a large number of illustrations of the work.

Stambler, Irwin, "Exploding Wires Likely to Find Many Uses", Space and Aeronautics, 34 (3), 48-51 (September, 1960). A-2-2-4

This article covers work being performed by a few companies on the study of exploding wires. Graphs are shown of voltage and current vs time for various wire sizes for the materials tungsten and aluminum. Various applications for exploding wire such as high-speed photography, energy sources for forming, and simulation of meteorite impacts are discussed. Temperatures in the neighborhood of 1,000,000 F and soft X-rays have been produced by this technique. The pressure pulse produced is more rapid than that found with high explosives.

Webb, F. H., Chase, N., Ernstene, Marshall, and Tollestrup, A., "Submicrosecond Wire Explosion Studies at Electro-Optical Systems, Inc.", presented at the conference on Exploding Wire, Boston, April 2-3, 1959. A-2-2-5

This paper describes a research study of the electrically exploded-wire phenomenon with special emphasis on explosions occurring in very brief time intervals. Electrical and optical observations have been made with a millimicrosecond Kerr cell camera. One wire-explosion circuit is composed of a capacitor of 2,000 $\mu\mu$f charged to between 10 and 20 kilovolts which is discharged into a circuit with a ringing period of 85 $\mu$sec by actuating a triggerable air spark gap. Generally 1-mil wires, 0.290 inch long, of aluminum, copper, silver, gold, nickel, and tungsten placed across a gap with parallel plane geometry are exploded in air at atmospheric temperature and pressure. Voltage and current of the wire and its products and generally a single frame Kerr cell camera photograph in known time synchronism are recorded simultaneously. Another wire-exploder circuit employing a thyratron switch has also been used. The experimental results are discussed.

"Hydrospark Forming Offers Control, High Accuracy", Steel, 147 (2), 92-94 (July 11, 1960). A-2-2-6

The article discusses how "underwater lightning" is produced and what work can be done with it. It includes quotes from E. W. Fedderson of Convair and H. J. Wagner of Battelle Memorial Institute as well as work being done in this field at Republic Aviation and General Electric. From experimentation at Convair, it was found that they could get more power by decreasing the voltage, increasing the capacitance and adding an initiating wire between the electrodes. The wave fronts could be formed by shaping the initiating wire.

Cross References.

A-1-3-4 Discussion of the basic technical understanding of the exploding bridgewire phenomenon.

F-2-1-1 Describes energy-transfer phenomena in electrohydraulic metal forming.

Electrical

Magnetic Coil. A-2-3

Birdsall, D. H., Ford, F. C., Furth, H. P., and Riley, R. E., "Magnetic Forming! What is it?", American Machinist, 105 (6), 117-121 (March 20, 1961). A-2-3-1

Electric energy in the form of a magnetic field can be converted into useful work in forming metal parts. Magnetic pulses lasting only six millionths of a second have caused plastic flow in hard bronzes and steel under conditions where the work would fracture under conventional forming rates. This result is obtained because magnetic forming is similar to other high-energy processes like explosive forming, and obtains the desirable properties that occur as a result of very rapid forming. When large objects are to be formed, explosives have the merit of avoiding investment in an electrical-energy source, but for objects of moderate size the magnetic-forming method seems more convenient and reliable.

Brower, D. F., "Magnetic-Pulse Forming", SAE Journal, 70 (2), 38-40 (February, 1962). A-2-3-2

Experiments to explore the use of high-intensity pulsed magnetic fields to form metal into useful shapes, and the development of a magnetic-pulse forming machine are discussed. Three coil field-shaper combinations are shown which illustrate the kind of work which may be performed. The General Atomic Magneform machine is described. The capacitor bank associated with this equipment is capable of storing 4500 foot-pounds of energy. The efficiency of and applications for this equipment are discussed.

Eshelman, R. H., "New Metalforming Techniques Brighten Future Designs", Iron Age, 188 (26), 48-49 (December 28, 1961). A-2-3-3

A general discussion of electrospark and electromagnetic forming is given. A new device referred to as a magnetic hammer is discussed. It consists of a conducting ring into which a current pulse is fed. When the hammer is held near a metal surface, the magnetic field of the ring is compressed then pushed against the surface. Several pictures are shown of thin metal parts which have been formed and also blanked by these operations.

Furth, H. P., and Waniak, R. W., "Some New Ideas in Magnetic Metal Forming", SAE Journal, 70 (2), 38-40 (February, 1962). A-2-3-4

Recent inventions aimed at extending the range of practical applications of the magnetic-forming technique are described. Magnetic hammers, procedure for magnetic pulling, direct-electrode contact, and the problems involved are discussed. The design principles for magnetic hammers are reviewed.

Langlois, A. P., "Metal Forming with Electromagnetics", ASTME Report No. SP 60-170, presented at the Creative Manufacturing Seminars (1960-1961). A-2-3-5

This paper presents the work which has been conducted at Convair on the development and use of an electromagnetic machine for fabrication of aircraft and missile components. The equipment has been used on a production basis for the swaging of control rods and terminals of cables. The magnetic field is generated by an energy source similar to that used for electrohydraulic-spark devices.

"Magnetic Forming", American Machinist/Metalworking Manufacturing, 104 (20), 95-96 (October 3, 1960). A-2-3-6

Gives pictures and description of a magnetic swaging machine presently in use at the Naval Research Laboratory. The equipment, which was designed by General Atomics Division of General Dynamics Corporation, is presently being used for the swaging of connectors on coaxial cable. The design of a special switch, referred to as a magneto-hydrodynamic switch, is shown. The special switch is used to bridge the spark gap by the initiation of a guide spark. A magnetic field created tends to distribute the discharge around the electrode surface thereby reducing erosion of the electrodes.

Langlois, A. P., "Electromagnetic Metal Forming", The Tool and Manufacturing Engineer, 46 (6), 105-108 (May, 1961). A-2-3-7

The author describes in detail the operation of this electromagnetic metal-forming device. At the end of the article he indicates some present and future applications of the process.

Harvey, G. W., and Brower, D. F., "Metal Forming Device and Method", U. S. Patent No. 2,976,907 (March 28, 1961). A-2-3-8

The purpose of this apparatus is to form metals rapidly by means of the energy from a varying magnetic field. A conductor placed in a varying magnetic field has a current induced in it, and the interaction between this current and the magnetic field produces a force. If the conductor is confined and the magnetic field is strong enough, the force will cause the conductor to deform.

Brower, F. D., "Forming with Magnetic Pulses", Machine Design, 34 (9), 144, 146, 148 (April 12, 1962). A-2-3-9

The author describes the work being done at General Atomics Division of General Dynamics in magnetic-pulse forming. He states that efficiencies, based on stored energy versus work done on aluminum cylinders, are in the range of 10 to 40 per cent. The simplicity of the machine makes it quite attractive – it has no moving parts. It is particularly useful for expansion of the central portions of long tubes. Magnetic forming has a slower strain rate than explosive forming, but this insures more uniform strain rates and metal flow.

"Magnetic-Pulse Forming", Aircraft Production, 24 (4), 112-114 (April, 1962). A-2-3-10

This article describes the work being conducted at General Atomics Division of the General Dynamics Corporation in magnetic-pulse forming. This new method of forming uses the energy developed in a magnetic field to work metals. "Field-shapers" are used to perform specific forming operations. It is possible to achieve fields up to 1,000,000 gauss or over 500,000 lbs/in.$^2$.

Cross References.

A-1-1-15 Outlines work in electromagnetic forming.

F-3-0-12 Reviews development of an electromagnetic unit (Magnepak).

## Energy Sources

### Mechanical A-3-0

Wood, William W., "High Energy Forming Methods - A Critical Review", The Tool Engineer, 44 (6), 93-105 (June 15, 1960). A-3-0-1

High-energy-rate forming methods, including high-mass systems, high-velocity systems, and high-temperature systems, are discussed. The author shows how each method works and suggests the materials and types of parts suitable for each method.

Cross References.

A-1-0-1 Discusses safety of mechanical high-energy-rate forming equipment and operations.

A-1-0-2 General coverage of mechanical high-energy-rate devices. These devices are compared with conventional forming equipment.

A-1-0-3 Reviews past accomplishments and points out areas where information is lacking in the field of mechanical high energy.

A-1-0-4 Describes mechanical high-energy-rate forming and compares it with conventional forming.

A-1-0-5 Gives limitations and applications of mechanical high-energy-rate forming and discusses the response of several metals to this process.

A-1-0-6 A nontechnical report which covers pneumatic-mechanical forming and closed-cavity extrusion molding.

A-1-1-3 Compares energy output of mechanical high-energy-rate forming devices with that of other high-energy-rate forming methods. Also gives unusual characteristics of the system.

A-2-0-6 Presents one viewpoint of the entire high-energy field. Discusses the pneumatic-mechanical method.

F-1-1-14 Discusses pneumatic-mechanical forming and mechanical-energy sources.

## Mechanical

### Compressed Gas. A-3-1

"Gas-Ram Machine Opens New Fields for Metal Forming", Product Engineering, 29 (46), 38 (November 10, 1958). A-3-1-1

This article gives some of the specifications and capabilities of Convair's gas-powered forming tool, the Dynapak.

Palsulich, Joseph M., and Headman, Martin L., "Developments in Pneumatic High Energy Rate Forging", ASTME Report No. SP 62-11, presented at Creative Manufacturing Seminars (1961-1962). A-3-1-2

This paper discusses the production forging work at Western Gear Corporation done with a Dynapak machine. This type of machine has advantages over conventional forging equipment in repeatability, reliability, workability, economy, and material conservation. The cycle time for the machine has been established at 18 seconds. The gas costs run between 3 and 4 cents a shot. The maximum output of the machine has been 500 parts in one eight-hour shift. Early difficulties with the machine have been eliminated.

"Forgings Made by High-Energy Process", Materials in Design Engineering, 54 (2), 17 (August, 1961). A-3-1-3

This article describes the operation of Convair's pneumatic-mechanical device, the Dynapak machine.

Riordan, Thomas S., "High-Energy-Rate Forming in Production at Bendix-Utica", ASTME Report No. SP 62-04, presented at Creative Manufacturing Seminars (1961-1962). A-3-1-4

This paper describes the application of a 1210 Dynapak machine in a production operation. In one year's time a total of 18,000 parts have been successfully formed. A considerable cost reduction in the manufacture of details was obtained through the use of this equipment. The major cost reduction was in the elimination of machining time. The parts produced were of close tolerance and had a minimum of scale due to elevated-temperature oxidation.

High Energy Rate Closed-Cavity Extrusion Molding, Brochure DPO-36, Convair, Fort Worth (December 14, 1960). A-3-1-5

This preliminary brochure indicates the current status of development and the future potential of high-energy-rate closed-cavity extrusion molding. Information is included on manufacturing research and development activities at Convair, Fort Worth, utilizing Dynapak equipment.

Dynapak High-Velocity Extruding, Forging, Forming, Compacting, Convair, Pomona, California. A-3-1-6

This brochure provides basic information on the various pneumatical-mechanical pieces of equipment marketed by Convair.

"Energy Alone Isn't the Answer – Speed of Release May Count Too", American Machinist, 101 (1), 114-115 (January 14, 1957). A-3-1-7

This article cites examples of typical energy storage and transmission devices presently used in forming equipment as evidence that the speed of release of energy is important. Typical values of energy release rate for steel are 7 or 8 foot-pounds up to 88 foot-pounds/sec, according to the shape of the steel. Compressed air at 3000 psi can deliver up to 50,000 foot-pounds per pound of energy.

"High Energy Pneumatic Machine Tool Forms Metal at 'Explosive' Velocities", American Machinist, 102 (24), 239-240 (November 17, 1958). A-3-1-8

This article describes the Dynapak machine made by Convair.

"Explosive Forming by Pneumatic Machine", Australasian Manufacturer, 44, 56, 58, 59 (September 12, 1959). A-3-1-9

The forming machine described provides energy up to 1,500,000 foot-pounds to make extrusions and forgings to close tolerances with good surface finishes.

"New One Step Forging Machine Presses for Higher Outputs", The Iron Age, 189 (4), 100-101 (January 25, 1962). A-3-1-10

Operation of the Clearing high-energy-rate-forging machine is described. Detailed sequence of action is illustrated. Cycle time for the machine is ten seconds. It will produce six finished forgings per minute. The press is 12 feet high, 6-1/2 feet wide, and 3 feet deep. Savings of up to 50 per cent over conventional equipment are claimed for the production of forgings on this machine.

"Gas Powers Metalforming Giant", The Iron Age, 187 (26), 74-75 (June 29, 1961). A-3-1-11

A discussion of the model 1810 Dynapak is given. The reported ram velocity for this machine is 250-1500 ips and the energy output maximum is 431,000 foot-pounds. The machine's maximum stroke length is 15 inches and its cycle time is 105 seconds. The maximum die size which can be used on this machine is 22.5 inches. Some information on forming a steel cap from a billet is presented.

"Plastic Deformation at High Velocity", Light Metals, 20 (233), 260-261 (August, 1957). A-3-1-12

This article describes in general terms some of the advantages in using a Dynapak-type machine rather than high explosives.

"Compressed Nitrogen Drives HERF Press", The Tool and Manufacturing Engineer, 48 (3), 90-91 (March, 1962). A-3-1-13

The operational characteristics of Clearing's new 2600B-forging pneumatic-mechanical device are presented. A cut-away view of the machine shows the sequencing during operation. Maximum impact speed is reported as 62 feet per second.

Carpenter, S. R., "High Energy Forming", Aircraft Engineering, 32 (372), 53-54 (February, 1960). A-3-1-14

The author first mentions the need for making use of the hydrodynamic properties which metals exhibit when subjected to high energies and rates of forming. He then discusses in detail the Dynapak machine made by Convair. Applications of the machine and some of the cost benefits derived from using it are discussed.

Carbonaro, P. A. G., and Valencia, S., "Cold Swaging Extends Design Horizons", The Tool Engineer, 44 (4), 113-117 (April, 1960). A-3-1-15

A cold-swaging process is described in this article. Tubular workpieces are reshaped by means of high pulsating pressure applications produced by rotating and simultaneously striking dies. The authors give a detailed description of the swaging machine, developed for the General Thomas J. Rodman Laboratory of the Watertown Arsenal. They also discuss the particular problem of swaging uranium.

Cross References.

A-1-1-15 General outline of work done in pneumatic-mechanical forming.

F-1-0-76 Study of early development of Dynapak at Convair.

F-3-0-5 Investigation of parameters that directly affect tensile failure during extrusion with mechanical devices.

F-3-0-12 Reviews development of the Dynapak pneumatic-mechanical equipment.

Mechanical

Liquefied Gas. A-3-2

## Energy Transfer Mediums

Anderson, J. R., and Nestler, D. E., "Shock Wave Propagation in Solids (A Survey of the Literature)", Project Frank, University of Pennsylvania, Contract NOrd 12772; AD 39616. B-0-1

This bibliography with abstracts deals with the following specific subject matter:

1. Dynamic photoelasticity
2. Longitudinal impact and the Hopkinson pressure bar
3. Electric strain gage
4. Explosive tests
5. Use of projectiles and high velocity fragments
6. High velocity testing machines
7. Velocity of wave parameters
8. Transient effects on the properties of materials.

Atkins, W. W., "Hypervelocity Penetration Studies", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). B-0-2

An empirical and theoretical study leading to the development of hypervelocity penetration equations is discussed. Terminal-ballistic effects useful in developing these equations are considered. The research was conducted at the U. S. Naval Research Laboratory.

Cross References.

F-1-2-1 Describes cratering in various metals and nonmetals.

## Energy Transfer Mediums

### Gases B-1

Allen, W. A., Mapes, J. M., and Mayfield, E. B., "Shock Waves in Air Produced by Elastic and Plastic Waves in a Plate", Journal of Applied Physics, 26 (1), 125-126 (January, 1955). B-1-1

This letter to the editor describes shock waves in air produced by elastic and plastic waves in a plate. Shadowgraphs are shown of these waves. Two shock waves are shown for brass but only one wave for copper. Results for steel and lead are also reported.

Deal, W. E., "Shock Hugoniot of Air", Journal of Applied Physics, 28 (7), 782-784 (1957). B-1-2

Experiments are described in which an explosive-driven plate sets up a strong shock wave in air in contact with the plate. Free-surface velocity and air-shock velocity were measured by means of a high-speed framing camera which viewed the plate in profile. Experimental results are shown for pressures up to 200 bars. A 24ST Dural plate is used.

Dorman, William J., and Brown, John A., "Meteorological Focusing of Sound and Blast Waves and Its Prediction by Analog Techniques", BRL Report No. 1014, Proj. No. TB3-0112, Ballistic Research Labs., Aberdeen Proving Ground, Maryland (April, 1957); AD 139250. B-1-3

Meteorological focusing can cause sound and blast waves resulting from the testing of large guns and explosives to be propagated at high amplitude over unusually large distances. Thus damage or other undesirable effects are obtained at locations normally thought to be at a safe distance from the testing site. Possible damage can be avoided by the cancellation of scheduled tests on days when the existing meteorological conditions are likely to produce focusing of the resulting blast waves. In this report the equations of the trajectory of a point in a blast wavefront are derived for the general case and modified for several special cases. A method is given for predicting meteorological focusing by means of an analog-computer solution of these equations with data obtained from soundings of the lower atmosphere.

"Air Blast from H-6, Comp B, DYX and DX Charges Base and Loaded in 100 lb. GP Bomb Cases", NAVOrd Report No. 3819, U. S. Naval Ordnance Laboratory, White Oak, Maryland (October 1, 1955); AD 79885. B-1-4

Peak pressure and positive impulse were measured for four different explosives.

Wall, T. L., "Assessment of Blast Damage to Simple Structures: Part 2, Estimation of Chamber Effect with Closed Cubes", Armament Research and Development Establishment, Great Britain (October, 1954); Tables reprinted as Report No. 25/24, Safety in Mines Research Establishment, Buxton Report No. E209. B-1-5

A series of experiments were carried out in which small charges of high explosive were detonated centrally in closed cubical steel boxes. These were suspended in free space and within confining chambers of various sizes. The amount of deformation of the cubes was taken as a measure of the damage. The size of the confining chamber was increased up to just greater than 12 times the linear dimensions of the cubical targets but conditions equivalent to free space were still not obtained.

"Comparison of Blast From Terrier Warheads Loaded with Comp. B and H-6", Denver Research Institute, University of Denver, Contract NOrd 11541 (December 30, 1954). B-1-6

This report gives peak pressure and impulse measurements and a comparison of fragment velocities from an air blast of terrier missile warheads with two different explosives. It also gives information on the instrumentation required for the measurements.

"Relative Air Blast Damage Effectiveness of Various Explosives", Memorandum Report 689 CLI053, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, ORD Project TB 3-0238 (June, 1953). B-1-7

This report gives results of air blast damage tests with the following explosives listed in decreasing order of effectiveness: Torpex 2, H-C, Tritonal, Comp B, Pentolite, and TNT.

Cross References.

B-2-3 Gives pressure and energy data for explosives in air.

B-4-38 The intensity and duration of explosively induced nonuniform oblique shocks are calculated for the cases involving supersonic flow in the explosive gas.

## Energy Transfer Mediums

### Liquids B-2

Bowden, F. P., and Brunton, H. J., "Damage to Solids by Liquid Impact at Supersonic Speeds", Nature, 181 (4613), 873-875 (March 29, 1958). B-2-1

A study was made of the deformation and damage sustained by metallic and plastic specimens subjected to impact by a cylinder of water of about 0.01 $cm^3$ in volume travelling at about 3100 feet per second. With a stainless steel specimen, impact produced a shallow saucer-shaped depression with a central pit and a highly deformed annular region just inside the rim of the depression. The area of deformation corresponded closely to the area over which the spreading cylinder exerted pressure. With an aluminum specimen, the area of the affected surface was similar to that with stainless steel, but the depression was ten times greater. The annular region with metals seemed to have been sheared open by water flowing at high speed over it. The intensity of this deformation increased with the viscosity of the liquid used. With plastic targets, the main feature of the damage was a ring crack on the surface and a central star crack below the surface. Sometimes rear scabbing also occurred. Under repeated impact, the cracks spread until a piece of plastic was dislodged from the surface. The flow of liquid parallel to the surface of the specimens was found to be between two and three times as great as the impact velocity.

Kennard, E. H., "Cavitation in an Elastic Liquid", Physical Review, 63 (5 and 6), 172-181 (March 1 and 15, 1943). B-2-2

An idealized theory of cavitation in the interior of a liquid is developed as an extension of the hydrodynamics of rotational motion. It is assumed that cavitation occurs whenever the pressure sinks to a fixed breaking-pressure and that the pressure then rises at once to a fixed cavity pressure. The boundary of the cavitated region either advances as a breaking-front moving with supersonic velocity, or remains stationary as a free surface, or recedes toward the cavitated region as a closing front. The relevant formulas are obtained.

"Explosive Effects Data Sheets", NavOrd Report No. 2986, U. S. Naval Ordnance Laboratory (June 14, 1955), AD 69244. B-2-3

Nomograms are given for pressure and energy for several explosives when the weight and distance from the point of detonation under water are known. The same data for explosives in air are presented. Peak pressure inside the closed box containing the explosives was measured.

## Energy Transfer Mediums

Solids B-3

Alter, B. E. K., and Curtis, C. W., "Effect of Strain Rate on the Propagation of a Plastic Pulse Along a Lead Bar", Journal of Applied Physics, 27 (9), 1079-1085 (1956). B-3-1

This is a very thorough article on the effect of strain rate on the velocity of propagation of a plastic wave in a bar. Tests were carried out to determine how pulses of plastic deformation disperse during propagation along a lead bar. The theory of rate of propagation is reviewed and experimental results are presented. The article contains a list of 20 references.

Blake, F. G., Jr., "Spherical Wave Propagation in Solid Media", The Journal of the Acoustical Society of America, 24 (2), 211-215 (March, 1952). B-3-2

Divergent compressional waves in solids differ from similar waves in fluids, even though the particle displacement is parallel to the direction of propagation in both media. The wave propagating from a radially-oscillating spherical cavity in an infinite-solid medium sees an acoustic-radiation impedance which is a function of the Poisson's ratio of the medium as well as of the usual parameters. The radiation resistance has the same form as in a fluid medium, but the reactance is a negative or stiffness reactance, except at high frequencies in media of low rigidity. When an impulsive pressure is generated in the cavity, as by an explosion, the form of the radiated pulse is a damped-oscillating wave train which does not closely reproduce the original pressure pulse.

Buchanan, J. S., James, H. J., Teague, G. W., "The Dynamic Compression of Perspex", Philosophical Magazine, Series 8, 3 (36), 1432-1448 (December, 1958). B-3-3

High explosives have been employed in determining the Hugoniot equation of state for Perspex in a pressure range from 3 to 13 x $10^{10}$ dynes per $cm^2$. Graphs are given of the variation of pressure, shock, and particle velocity with Perspex thickness.

Cann, G. L., "Non-Linear Waves in Solids", Canadian Symposium on Aerodynamics Proceedings, 2, 238 (February, 1954). B-3-4

General one-dimensional conservation laws for plastic flow of a bar are derived in Lagrangian coordinates. The equations of von Karman and Malvern are derived as special cases. A detailed solution is given for the case of longitudinal impact with constant velocity assuming work-hardening to be a function of plastic work. Plastic-shock waves do not travel at speeds less than those of elastic waves.

Clay, W. G., and Partridge, W. S., "Wax Modelling Studies of High-Speed Impact", Technical Report OSR-5, OSR TN-56-257, University of Utah, Salt Lake City, Contract AF 18(600)-1217, AD 88977. B-3-5

An investigation of wax-to-wax impact is presented in an attempt to "model" high-speed impact of metal into metal. Wax is chosen as the modelling substance because of its comparatively low-sonic velocity and the physical similarity of wax craters to craters formed at the impact of metal into metal. The sonic velocity in wax is determined as a function of temperature; the work reported is made with the wax targets at a temperature of about 75 F, at which the sonic velocity in wax is approximately 0.7 kilometers per second. A method of accelerating wax pellets by means of laboratory guns is given; also, use is made of the static charge on wax pellets in some of the velocity measurements. The penetration of the impacting pellet is found to vary linearly with the cube root of the pellet mass and the pellet velocity to velocities in excess of twice the sonic velocity in the wax target. The crater area varies directly as the pellet area and the velocity, both below and above the sonic velocity, but there is a marked increase in the constant of proportionality above the sonic velocity. The volume of the crater per unit energy of the pellet is discussed, and it is found that in wax this characteristic is not independent of velocity. Values of volume per unit energy range over $1.5\text{-}4.0 \times 10^{-8} m^3/j$, over the velocity range zero to 2 kilometers per second. Experiments are described which throw some light on the mechanisms of cratering. It is observed that a large part of the crater volume is created by deformation of the target material, and that only a small part is due to ejection of target material. There is an apparent cavitation in the target material surrounding the crater, probably caused by a shock wave created by the impact. A comparison of features of wax craters with metal craters indicates validity of the wax model.

Jacobs, S. J., "Recent Advances in Condensed Media Detonations", American Rocket Society Journal, 30 (2), 151-158 (February, 1960). B-3-6

Present analyses of shock-wave propagation in metals are being considered, with few exceptions, as fluids when the compressions are large. This simplification has enabled the solution of many problems related to condensed detonation. It is concluded, however, that there are many examples in which this assumption does not lead to useful answers. Likewise the effect of prior compression on solid fuels and its relation to the transition to detonation problems is an area of considerable interest.

James, H. J., Buchanan, S. S., and Teague, G. W., "The Dynamic Compression of Some Non-Metals", Ministry of Supply, A. R. D. E. Report (MX) 12/19 (July, 1959). B-3-7

Experiments of shock waves in polyethylene and rubber are described. The Hugoniot equation of state was determined for a pressure $3\text{-}13 \times 10^{10}$ dynes per $cm^2$. Graphs of pressure, shock, and particle velocity with thickness of material are given and discussed.

von Karman, Theodore, and Duwez, Pol, "The Propagation of Plastic Deformation in Solids", Journal of Applied Physics, 21 (10), 987-994 (October, 1950). B-3-8

The stress wave caused by a longitudinal impact at the end of a cylindrical bar has been analyzed in the case where the impact velocity is large enough to produce plastic strain. The theory gives a method for computing the stress distribution along the bar at any instant during impact. It is shown that for a given material, there is a critical impact velocity such that when subjected to a tension impact with a velocity higher than the critical, the material should break near the impacted end with negligible plastic strain.

An experimental investigation was made concurrently with the theoretical study. Some very significant experimental results are presented in this paper.

Kal'ner, D. A., "Methods of Determining the Relationship Between the Propagation Velocities of Plastic and the Elastic Deformation", Zavodskaya Laboratoriya, 22 (9), 1086 (September, 1956). In Russian. B-3-9

A method of computing the velocity of plastic deformation in a material is given.

Katz, Samuel, Curran, D. R., and Doral, D. G., "Hugoniot Equation of State of Aluminum and Steel from Oblique Shock Measurement", Poulter Laboratories Technical Report 025-57, Stanford Research Institute, Menlo Park, California (December 9, 1957), AD 234962. B-3-10

A new method for determining the Hugoniot equation of state of solids is described. The method uses an oblique shock in a wedge-shaped specimen, cut so that the oblique shock is incident at an angle close to normal over the wedge face. The oblique shock is produced by a slab of explosive, lying on top of the wedge and line-initiated, providing essentially a two-dimensional shock. Simultaneous measurement of shock and free-surface velocities down the wedge face provides the data for calculation of the Hugoniot pressure and density over a wide range on a single shot. In aluminum a pressure range exceeding 2:1 may be observed on a single shot. The pressure range for which data were obtained was from 180 kb to 40 kb. Information was also obtained on low-carbon steel.

Koehler, J. S., and Seitz, F., "The Stress Waves Produced in a Plate by a Plane Pressure Pulse", OSRD-3230 (January, 1944); ATI 25115. B-3-11

The behavior of an infinite plate of finite thickness having one face subjected to a plane-pressure pulse was investigated. In this pulse, the pressure rises suddenly, remains constant for a time, and then drops off exponentially. The other face of the plate is not under pressure. If high pressures are present in the pulses (that is, above about 5 x $10^5$ psi in steel) plastic shock waves will be produced. The velocity of the plastic-shock wave is calculated and the effect of high pressure on the velocity of the release wave is determined. A criterion is established that enables one to distinguish between "thick" and "thin" plates. The displacements and stresses found in thick and thin plates at various times are determined.

Kolsky, H., Stress Waves in Solids, Oxford Clarendon Press, New York (1953). B-3-12

This monograph gives a concise account of the classical theory of stress waves in solids, how this theory has been extended to solids which are not perfectly elastic, and summarizes the experimental work carried out in recent years. The mathematical analysis given is plain and easy to follow. Some of the areas covered are propagation in an extended elastic medium; propagation in bounded elastic media, experimental investigations with elastic materials, and stress waves in imperfectly elastic media.

Mason, P., "High-Speed Fracture in Rubber", Journal of Applied Physics, <u>29</u> (8), 1146-1150 (August, 1958). B-3-13

Cinematographic observations have been made of crack propagation under well-defined boundary conditions in rubbers at speeds up to 30 meters per second. The fracture markings showed resemblances to those obtained with metals, plastics, and glass, and could be related directly to the corresponding speed of fracture propagation. In close analogy with Schardin's observations on glass, a non-crystallizing rubber (GR-S) showed a mode of crack propagation in which the fractured surfaces were visually smooth and the speed was about one quarter of the speed of longitudinal elastic waves. A crystallizing rubber (natural rubber) did not show this mode of propagation under the present test conditions. It is suggested that the modes of solid fracture can be usefully classified in three categories: (1) slow propagation, generally with smooth surfaces, obtained by careful control of the boundary conditions; (2) propagation at intermediate rates with rough surfaces, involving correspondingly greater energy consumption; and (3) fast propagation with smooth surfaces, the rate of propagation being limited by the speed of elastic waves in the material in accord with Mott's theory.

LaRocca, E. W., "Making Compacts by Explosive Forming", Metal Progress, <u>76</u> (3), 85-86 (September, 1959). B-3-14

The paper summarizes the well-known laws which govern the reflection of elastic waves that strike free surfaces obliquely. These laws are used to deduce particle motion at the free surface. A number of numerical computations are presented in tables and graphs for the case of an incident longitudinal wave. Considerations indicate that for oblique incidence, the particle motion will not generally be perpendicular to the surface. Data included in this paper are expected to be of value in the solution of problems connected with impulsively loaded bodies such as metal-explosive systems.

Pearson, J., and Rinehart, J. S., "Surface Motion Associated with Obliquely Incident Elastic Waves", Journal of the Acoustical Society of America, <u>25</u> (2), 217-219 (March, 1953). B-3-15

Well-known laws which govern the reflection of elastic waves that strike free surfaces obliquely are used to deduce particle motion at the free surface of a body. The data are expected to be of value in the solution of problems connected with impulsively loaded bodies such as metal-explosive systems.

Cross References.

B-0-1 Deals with shock-wave propagation in solids.

B-4-8 Covers behavior of brass plates under impact loading.

B-4-29 Analyzes explosive production of plane shock waves in solids.

B-4-30 Analyzes explosive production of oblique waves in solids.

B-4-38 Assumes metals under explosive attack act like nonviscous, non-heat-conducting fluids and calculates the intensity and duration of the non-uniform oblique shocks in the metal based on these assumptions.

B-4-40 Directional variation of body-wave velocities have been computed for cubic and hexagonal metals.

B-4-50 Treats theory of propagation of plastic waves in one dimension.

D-1-1 Theory of a method of test is given, and the results of tests on two resin materials are included.

E-2-27 Presents problems of testing materials at high speed.

F-1-8-5 Discusses use of alluvial sand as a shock-transmitting medium at elevated temperatures.

F-3-0-3 State-of-the-art survey of rubber pad forming of sheet materials.

F-3-0-4 Discusses the use of trapped rubber explosive forming.

## Energy Transfer Mediums

### Shock Wave Propagation B-4

Allen, W. A., and McCrary, C. L., "Transient Waves Through Steel Produced by Impulsive Loading", Paper presented at meeting of American Physical Society, Berkeley, California (December 27-29, 1951). Abstract in the Physical Review, 85 (4), 769 (1952). B-4-1

The transient behavior of a thick circular plate deforming under explosive attack has been investigated. An experimental technique, based upon the principle of the optical lever has been used to measure surface oscillations as small as 10 $\mu$, in amplitude. Measured particle velocities determined by this method indicated the presence of elastic and plastic waves.

Allen, W. A., and McCrary, C. L., "Experimental Technique Used to Measure Transient Waves Through Solids", The Review of Scientific Instruments, 24 (2), 165-171 (February, 1953). B-4-2

An experimental technique, based upon the principle of the optical lever, has been used to measure surface oscillations as small as 10 microinches in amplitude on a thick circular plate, while it deforms under explosive attack. The transient behavior of the plate was determined by means of a long focal-length, sweeping, image camera with a writing speed of four millimeters per microsecond. In comparison with the Hopkinson method, the technique yields more information of equivalent, or greater, accuracy. Equations are derived that have been used in the analysis of the experimental data. Experimental results are given as an indication of the precision of the technique.

Allen, William A., "Elastic Description of a High-Amplitude Spherical Pulse in Steel", NOTS TM N. 994, U. S. Naval Ordnance Test Station, Inyokern, China Lake, California (April 21, 1953). B-4-3

Extensive calculations are performed with the IBM-card-programmed electronic calculator to evaluate a problem in elasticity that simulates the effect of a cylindrical charge detonated in intimate contact with a steel plate. Although elastic theory has been extrapolated into a regime where it is known not to apply, insight can be obtained on the origin of the negative component of the pulse which produces tensile fracture in the specimen. Agreement between experiment and elastic theory improves as the stresses decay to sonic proportions.

Allen, William A., "Free Surface Motion Induced by Shock Waves in Steel", Journal of Applied Physics, 24 (9), 1180-1185 (September, 1953). B-4-4

An optical technique, reported in a previous paper, has been used to measure surface oscillations on a series of 5.5-inch-diameter steel plates of different thicknesses while they deform under explosive attack. Data obtained from the four 1025 steel specimens illustrated in the previous paper, and data obtained from two additional specimens have been analyzed partially. Results are compared with predictions from the theory of elasticity for the case of a diverging pulse. Elementary theory, known to be incorrect in the physical regime studied, is shown to give many satisfactory predictions for large distances from the charge.

Allen, William A., and Goldsmith, W., "Spall Effects Produced by a Cylindrical and a Spherical Charge of High Explosive", Journal of Applied Physics, 25 (6), 813-814 (1954). B-4-5

A letter to the editor discusses the feasibility of using a spherical charge in replacement for a cylindrical charge in determining spall effects on the free surface of a plate.

Allen, W. A., and Goldsmith, W., "Elastic Description of a High-Amplitude Spherical Pulse in Steel", Journal of Applied Physics, 26 (1), 69-74 (January, 1955). B-4-6

Extensive calculations have been performed with an electronic calculator to evaluate a problem in elasticity that simulates the effect of a cylindrical charge of high explosive detonated in intimate contact with a steel plate. The general method of calculation has been described in detail. Although elastic theory has been extrapolated into a regime where it is known not to apply, insight of a valuable general nature has been obtained on the nature of the negative component of the pulse.

Allen, W. A., Morrison, H. L., Ray, D. B., and Rogers, J. W., "Fluid Mechanics of Copper", Proceedings Third Symposium Hypervelocity Impact, Chicago, October 7-9, 1958, Vol 1 (February, 1959). B-4-7

Equation-of-state data has been obtained by impacting copper with a copper projectile. The compressible phase of the problem, involving flow of an arbitrary inviscid compressible fluid around an infinite wedge, is discussed. The incompressible phase, involving the impact of two fluid jets, is only mentioned.

Becker, H., "On Shock Propagation in Brass", Journal of Applied Physics, 25 (8), 1066-1067 (August, 1954). B-4-8

By replotting the work of Shreffler and Deal a clearer picture of the behavior of brass plates under impact loading was obtained. Demarcation zones are indicated on the new plots revealing cut-off thickness values at which velocity ranges in the thicker plates are no longer possible in the thinner plates.

Bell, J. F., "Theoretical and Experimental Studies of Plastic Wave Propagation in Longitudinal Rods Subject to Impact", Johns Hopkins University, Contract No. DA-36-034-ORD-2366 (1956). B-4-9

A new method employing diffraction gratings of very short length will be utilized to study propagated plastic wave fronts of large magnitude. Unloading waves, reflected waves from fixed and free ends, and a dynamic determination of Poisson's ratio are discussed.

Bell, J. F., "Determination of Dynamic Plastic Strain Through the Use of Diffraction Gratings", Journal of Applied Physics, 27 (10), 1109-1113 (1956). B-4-10

A new method is given for measuring dynamic-plastic strain in metals under central impact. Strain-time curves for initial and reflected-wave fronts have been determined using a gage length of 1/32 inch. The measurements are made by observing the behavior during strain of the diffracted and central images of an 8300-line-reflection grating ruled on the specimen surface.

Bell, J. F., "A Study of Initial Conditions in Constant Velocity Impact", Journal of Applied Physics, 31 (12), 2188 (December, 1960). B-4-11

A discussion is given of the results of making defraction-grating measurements of dynamic plastic strain within a few thousandths of an inch from the impact face of one-inch diameter, annealed aluminum specimens in free flight undergoing constant velocity impact. From these data it has been established that initial nondispersive-shock fronts are present, even in low-velocity impact. It is shown that the dynamic stress-strain curves obtained experimentally in annealed aluminum and copper may be computed directly from the theory, using information supplied by the static stress-strain curve. The von Karman critical velocity for annealed aluminum is found to be a dividing point between two types of initial wave development.

Bell, J. F., "The Diffraction Grating Strain Gauge", Proceedings Society for Experimental Stress Analysis, 17 (2), 51 (1960). B-4-12

A detailed discussion of the optical method for measurement of strain is developed by the author. Some of the advantages of this technique are: (1) either static or dynamic strains from very small to large can be measured on a single gauge; (2) accurate measurements of strain may be made at elevated temperatures; (3) this method may be used to determine the surface angle and the strain gradient simultaneously; (4) gauge lengths down to 0.001 inch are feasible; (5) accuracies of better than five per cent may be achieved; (6) the gauge may be calibrated in place; and (7) measurements of strain in moving projectiles or machine elements may be made without the necessity for electrical contact with the moving member.

Bell, J. F., "Propagation of Large Amplitude of Waves in Annealed Aluminum", Journal of Applied Physics, 31 (2), 277-282 (February, 1960). B-4-13

A study of large-amplitude compression waves for the case of constant-velocity impact gives close agreement with the strain-rate independent theory of one-dimensional plastic-wave propagation. Propagation velocities, maximum strain, and energy considerations agree with predictions from the slopes of the static stress-strain curve.

Bell, J. F., "An Experimental Study of the Unloading Phenomenon in Constant Velocity Impact", Journal of The Mechanics and Physics of Solids, 9 (1), 1-15 (1961). B-4-14

The coefficient of restitution, time of contact, and plastic strain distribution are determined experimentally for finite lengths of annealed aluminum rods for the case of two identical specimens in free flight collision. These data are found to be in agreement with the strain-rate independent theory of plastic-wave propagation in which an elastic wave of a magnitude given by the elastic unloading of the static stress-strain curve is reflected from the free end.

Brinkley, S. R., Jr., and Kirkwood, J. G., "Theory of the Propagation of Shock Waves", Physical Review, Series 2, 71 (9), 606-611 (May, 1947). B-4-15

A theory of propagation of one-dimensional shock waves is described. The partial differential equations of hydrodynamics and the Hugoniot relation between pressure and partial velocity are used to provide three relations between the four partial derivatives of pressure and partial velocity, with respect to time and distance from the source, at the shock front. An approximate fourth relation is set up by imposing a similarity restraint on the shape of the energy-time curve of the shock wave and by utilizing the second law of thermodynamics. Methods of determining at an arbitrary distance the distribution of the initial energy input between dissipated energy residual in the fluid already transversed by the shock wave and energy available for further propagation are given.

Zener, C., and Holloman, J. H., "Addendum to von Karman's Theory of the Propagation of Plastic Deformation in Solids", NDRC Memoranda No. A-37M (June, 1942); ATI 25158. B-4-16

Suggests modification of von Karman's original theory of the propagation of plastic deformation in solids based on experiments of Duwez. It is contended that the modification makes calculations simpler and brings theoretical predictions into harmony with experimental data.

Broberg, K. B., "Shock Waves in Elastic and Elastic-Plastic Media", Kunglia Fortifikation fur Valtningen Befästningsbyran, Rapport (109-12), p 141 (1956). Library of Congress, PB 126210. B-4-17

This report gives an interesting review of experiments on the propagation of elastic, plastic, and shock waves produced by impact and by the detonation of explosive charges. The theory of wave propagation is discussed and the propagation of spherically-divergent stress-waves is treated in detail. Tables of numerical values of dynamic stress-strain results for metals and other solids are presented. The fractures produced by the reflection of intense stress waves at the free boundaries of a specimen are described and discussed. The bibliography contains 71 references in the field, most of which are recent. (Abstract as given in Applied Mechanics Review.)

Burr, A. H., "Longitudinal and Torsional Impact in a Uniform Bar with a Rigid Body at One End", Journal of Applied Mechanics, 17 (2), 209-217, 462-465 (June, 1950). B-4-18

A uniform bar carrying a rigid body at one end is analysed for those cases where its other end is struck by a rigid body and by a bar and body, and for the case of sudden application of force at either end. Recurrence formulas are derived in non-dimensional form and applied to determine in a finite number of terms the stress equations for striking impact and for a constant force impact. Some useful theorems and simplifications, applicable to other problems of this nature, are indicated. For striking impact by a rigid body, charts show the time variation of stress and the maximum stress for a range of physical values of the bar and bodies. Application to the design of bars, helical springs, and shafts are discussed.

Wood, D. S., "On Longitudinal Plane Waves of Elastic-Plastic Strain in Solids", Journal of Applied Mechanics, ASME Transactions, 74, 521-525 (March, 1952). B-4-19

This article presents a theoretical description of the subject and a computation of the velocities of propagation of hydrostatic-compressibility waves in 24st aluminum alloy. Several curves and formulae are presented to help illustrate the findings. The author starts with the equation of motion and covers stress-strain relation, specific-wave-propagation problems, variable-compressibility effects, temperature variations, and time and rate effects.

Clark, D. S., "The Propagation of Plasticity in Uniaxial Compression", Journal of Applied Mechanics, ASME Transactions, 71, 219-221 (June, 1949). B-4-20

This article discusses another paper entitled "Stresses and Displacements in a Semi-Infinite Elastic Body with Parabolic Cross Section Acted on by Its Own Weight Only". Several points of disagreement are apparent. Curves and photographs are used to help demonstrate the author's discussion of the subject. The work mainly deals with small-diameter cylinders of lead which were fired at various velocities and the resulting deformation is used in deducing the stress involved.

Crede, C. E., "The Effect of Pulse on Simple Systems Under Impulsive Loading", Transactions of the American Society of Mechanical Engineers, 77 (6), 957-961 (August, 1955). B-4-21

This paper proposes modified parameters for presenting "shock spectra" for elastic systems acted upon by acceleration pulses. It is shown that the ratio of maximum response acceleration to maximum acceleration of the pulse is a function of the pulse shape. By introducing a parameter which includes velocity change of the pulse and the natural frequency of the elastic system, in place of maximum acceleration of the pulse, the influence of pulse shape on the spectrum is reduced materially. The significance of the spectrum for lightly damped systems is considered where failure may result from fatigue after many cycles of stress reversal induced by single pulses.

Cristeacu, N., "European Contributions to Dynamic Loading and Plastic Waves", Proceedings Second Symposium Naval Structural Mechanics (1960). B-4-22

A review of the European works concerned with longitudinal waves in thin bars, the finite bar, non-homogenous media, the influence of strain, and the propagation of the perturbations in strings is presented. Articles published in the interval 1945 to 1959 are included.

Davids, N., "Some Problems of Transient Analysis of Waves in Plates", International Symposium Stress Wave Propagation Materials, Interscience Publisher, Inc., New York (1960). B-4-23

This report is a review of some recent theoretical and experimental work at Pennsylvania State University on scabbing in materials. An analysis is made of the propagation of a transient stress pulse from a point on the boundary of a plate whose thickness is of the order of a wave-length. Spherical expansion of the source wave in the immediate neighborhood of the load is examined.

Davids, N., and Kumar, S., "Cylindrical Stress Waves in Flat Slabs", Quarterly Journal Mechanics and Applied Mathematics, 10 (4), 465-487 (November, 1957). B-4-24

After developing Goodman's solution for rapidly symmetric modes of stress-wave propagation in infinite slabs, this paper gives a detailed analysis of the determination of the various modes. Curves of both the non-dimensional phase and group velocities are given for Poisson's ratio from zero to one-half. The form of excitation at the center is discussed as well as the limiting cases for thin slabs and surface waves.

Davies, R. M., "Stress Waves in Solids", Applied Mechanics Review, 6 (1), 1-3 (January, 1953). B-4-25

This paper is a brief bibliography and review of literature concerning the transmission of stress waves in solids. It covers elastic wave propagation, visco-elastic-wave propagation and plastic-wave propagation.

Dennison, Bancroft, Peterson, Eric L., and Minshall, Stanley, "Polymorphism of Iron at High Pressure", Journal of Applied Physics, 27 (3), 291-298 (March, 1956). B-4-26

Propagation of compressive waves generated by high explosive in Armco iron may, under certain conditions, occur with three stable shocks, which are characterized by abrupt and possibly quasi-discontinuous change of pressure. The characteristics of these have been investigated experimentally and found to be consistent with the hypothesis of a polymorphic transition in iron at about 0.13 megabar. The same phenomenon has been observed in mild steel.

Donnell, L. H., "Longitudinal Wave Transmission and Impact", Transactions of American Society of Mechanical Engineers, 52 (Part I), 153-167 (1930). B-4-27

When force is applied to a body, waves of stress and velocity radiate through the body from the point of application of the force. When these waves strike the boundaries of the body, they may be wholly or partially transmitted to the surrounding bodies or reflected back into the body, where they reverberate back and forth within its confines, like sound waves within the body of air in a closed room. By superposition of these radiated and reflected waves the stress and motion of all parts of the body are graphically, and in general discontinuously, brought up to the values ordinarily assumed.

In the case of a small body this whole process takes place so quickly that there is great difficulty in detecting it (generally it is of little practical importance). But there

are cases where it is desirable to study the process in detail, particularly when the dimensions to be dealt with are no longer very small compared to the velocities of such waves and in consequence the time element is no longer negligible, or where the time of application or variation of applied forces is very small and hence of the same order of magnitude as the aforementioned time element, as in the cases of impact or harmonic forces of considerable frequency. In the present paper an attempt is made to consider some of the more important phases of this subject in as simple a manner as possible.

Drummond, W. E., "Multiple Shock Production", Journal of Applied Physics, 28 (9), 998 (September, 1957). B-4-28

A dynamical theory is given for the explosive production of multiple shocks in metals which undergo a phase transition. In addition to the formation of two compressive shocks, it is found that a rarefaction shock is also produced which will overtake one of the compressive shocks.

Drummond, William E., "Explosive Induced Shock Waves, Part I Plane Shock Waves", Journal of Applied Physics, 28 (12), 1437-1441 (1957). B-4-29

The explosive production of plane shock waves in solids is analyzed using the approximation that third and higher order terms in the shock strength can be neglected, and a procedure is developed for calculating the attenuation of the shocks. Application is made to the problem of determining the equation of state of the burned explosive gas.

Drummond, W. E., "Explosive-Induced Shock Waves, Part II Oblique Shock Waves", Journal of Applied Physics, 29 (2), 167-170 (February, 1958). B-4-30

The explosive production of oblique shock waves in solids is analyzed in the approximation that third and higher order terms in the shock strength can be neglected, and a procedure is developed for calculating the attenuation of the shocks. Application is made to the problem of determining the equation of state of the burned explosive gas.

Duvall, George E., "Some Properties and Application of Shock Waves", Poulter Laboratories, Stanford Research Institute, Menlo Park, California. B-4-31

This paper is ideally suited for the introduction of the nonspecialist to the shock-wave concept. It covers in broad terms how shock waves behave, furnishes some simple tools for exploratory calculations, and describes some experimental studies which may be important to the metallurgist or solid state physicist.

Duvall, G. E., and Zeolinski, B. J., "Entropic Equations of State and Their Application to Shock Wave Phenomena in Solids", Journal of the Acoustical Society of America, 27 (6), 1054-1058 (November, 1955). B-4-32

The hydrodynamic theory is used to calculate explicitly the entropy increase across a shock front, the amount by which the pressure exceeds the adiabatic pressure for a given compression, and the temperature rise after the shock pressure has been relieved for aluminum, copper, iron, and lead.

Duwez, P. E., and Clark, D. S., "An Experimental Study of the Propagation of Plastic Deformation under Conditions of Longitudinal Impact", American Society for Testing Metals Proceedings, 47, 502-532 (1947). B-4-33

The theory of plastic strain propagation is reviewed with reference to longitudinal impact. Special impact testing equipment is described by which data have been secured for the verification of the theory. Tests in tension on long wires and on specimens with a gage length of eight inches are reported, togerher with the results of some tests made in compression. The effect of release of loading and reflection of plastic-strain waves on plastic-strain distribution are considered. The concept of critical velocity is discussed. The anomalous behavior of material for which there is a yield point is presented. The results indicate very satisfactory agreement between theory and experiment.

Duwez, P. E., Wood, D. S., and Clark, D. S., "The Propagation of Plastic Strain in Tension", Progress Report No. A-99, National Defense Research Committee (October 5, 1942); AD 27727. B-4-34

Von Karman's theoretical considerations on the propagation of plastic strain was tested. The experiments provide data on the shape of the plastic-wave front in the case of copper and aluminum wires, on the reflection of the plastic strain from the fixed end of the copper wire specimen, and on the effect of impact velocity on the strain distribution, total elongation and total energy for annealed and hard-drawn copper and aluminum specimens eight inches long. The shape of the wave front is complicated because of the change through which the plastic-strain distribution passes during the unloading period. There is definite evidence of a reflection of plastic strain from the fixed end of a specimen of finite length. There is a definite effect of impact velocity on the total elongation and energy of an eight-inch specimen. The absolute values of the experimental and theoretical critical velocities are at variance.

Duvall, George F., "Some Properties and Applications of Shock Waves", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishing, New York (1961), p 165-203. B-4-35

Detonations and the shock waves they produce in inert materials are described qualitatively. Equations of the shock transition are given and applied in an example to obtain the amplitudes of shocks produced in several solids. Methods for measuring the equations of state of solids with shock waves are described and the reflection of a shock wave at a free surface is discussed. It is shown how phase transitions in materials give rise to multiple shock waves and how these in turn can be used to study transitions.

Eckel, K., "Practicability of Detonation and Shock Wave Analysis for High Energy Rate Forming", Lockheed Aircraft Corporation Report No. MAS 57 (February 14, 1958). B-4-36

The physical problems involved in the experiments of high energy-rate forming are examined in order to find out how far they can be solved by mathematical analysis. All phenomena of detonation and shock waves in the experiments of high-energy-rate forming can be predicted by solving the correspondent differential equations of supersonic flow. The effort will be comparatively small, if the problems can be specified in such a way that only one-dimensional unsteady flow or two-dimensional steady flow must be considered. The theory of supersonic flow is well developed for these cases and several studies concerning one-dimensional problems of detonation and shock waves have been published.

Elder, F. K., Jr., "Shock Wave Bibliography of Periodical Literature", AD 12032, Armed Services Technical Information Agency (March, 1953). B-4-37

Current periodical literature on the physics of shock waves, published during the period 1920 to 1952, is covered. Reference sources include Physics Abstracts, Engineering Index, the Industrial Arts Index, the bibliography section of the Journal of the Acoustical Society of America, and the volume indexes to the Physical Review. References to papers contributed at the American Physical Society meetings are also given.

Erkman, J. O., "Explosively Induced Nonuniform Oblique Shocks", Physics of Fluids, 1 (6), 535-540 (November-December, 1958). B-4-38

By assuming that metals under explosive attack behave like nonviscous, non-heat-conducting fluids the intensity and duration of explosively-induced nonuniform oblique shocks are calculated for aluminum and copper in those cases involving supersonic flow (isotropic even in the presence of shock waves) both in the metal and explosive gas. Results for oblique shocks confirm the results obtained for plane shocks.

Gilhamet, J., and Goldsmith, W. (Translators), "Propagation of Plastic Strain", University of California, Institute of Engineering Research (July, 1953). B-4-39

Translations of five articles from Russian and French are presented:

1. Altschuler, V., "On Explosions in a Compressible Plastic Medium"
2. Danilovskaya, I., "Concerning a Dynamic Problem of Thermoelasticity"
3. Bakhshian, R. A., "Elasto-Plastic Waves of Loading"
4. "Rakhmatulin, Kh. A., "The Propagation of Cylindrical Waves of Plastic Deformation (Torsional Impact)"
5. Luntz, Ya. L., "The Propagation of Spherical Waves in an Elasto-Plastic Medium".

Gold, L., "Compilation of Body-Wave Velocity Data for Cubic and Hexagonal Metals", Journal of Applied Physics, 21 (6), 541 (June, 1950). B-4-40

Directional variation of body-wave velocities have been computed for cubic and hexagonal metals where stiffness coefficients are known. A stereographic-coordinate system is used to present data for cubic metals in the form of isovelocity contours for the three wave vectors. Compressional and shear velocities for hexagonal metals are plotted as a function of the angle between the direction of wave propagation and the hexagonal axis.

Goldsmith, Werner, "Spherical Wave Propagation in Isotropic Elasto-Plastic Media", Institute of Engineering, University of California, Berkeley (July, 1953), Contract No. N123S-68742; AD 24632, Rpt Number Series 63, issue 3. B-4-41

This discussion is concerned with an additional examination of the problem of spherical wave propagation in media exhibiting both elastic and plastic characteristics. The nature of the governing differential equations necessitates the use of some severely restrictive assumptions in order to permit an analytical approach to the problem. Extensive investigations are required to ascertain the degree of approximation employed as contrasted to a more rigorous solution.

The differential equations of elasto-plastic wave propagation have been derived for a medium whose static stress-strain curve consists of two straight lines under the assumption that (a) displacements can be regarded as infinitesimal and (b) that the ratios of radial to tangential stress remain constant throughout the medium. While a particular solution of this equation has been obtained, this solution cannot be applied to the case when the boundary conditions involve the specification of a pulse at the initial radius as well as the continuity requirement of displacement at the plastic front. However, the velocity of propagation of this front has been established.

Goldsmith, W., and Allen, W. A., "Graphical Representation of the Spherical Propagation of Explosive Pulses in Elastic Media", Journal of the Acoustical Society of America, 27 (1), 47-55 (January, 1955). B-4-42

Analytic expressions of displacements (velocities and stresses as a function of location and time), as solved with the use of an IBM machine, are presented in pictorial form. Presentation is applicable to spherical-divergent waves in homogeneous, isotropic, elastic media of infinite extent under the waves generated by an explosion on one face of the medium. Graphs permit a rapid evaluation of the nature of the disturbance.

Hauser, F. E., Simmons, J. A., and Dorn, J. E., "Strain Rate Effects in Plastic Wave Propagation", Third Technical Report, Series No. 133, Issue No. 3, Materials Research Laboratory, University of California, Berkeley (June, 1960). B-4-43

This paper presents a method by which the plastic properties of materials can be investigated at strain rates up to $1.5 \times 10^4$ per second through impulsive-loading techniques. The stress-strain-rate properties of high-purity aluminum are presented for

295 K, 194 K, and 78 K over strain rates from 2 to 12,000 per second. Comparison is made between the elasto-plastic and strain-rate theories showing that elasto-plastic theory cannot account for plastic behavior for the range of strain rates obtained and that the customary Malvern strain-rate theory fails to properly take account of structure in determining strain-rate effects. A description is given of strain-rate effects in terms of dislocation theory and existence of a limiting strain rate is deduced from dislocation processes.

Hunter, S. C., "The Propagation of Spherically Symmetric Disturbances in Ideally Plastic Materials", Proceedings of the Conference on the Properties of Materials at High Rates of Strain, Institution Mechanical Engineers (April-May, 1957). B-4-44

The general solution of the equations of dynamic plasticity for the propagation of spherically symmetric disturbances of small amplitude is expressed in terms of the solutions of the wave equation. The continuity conditions across a boundary dividing a plastically deforming region from an elastically deforming region are established.

Hunter, S. C., "Some Notes on the Propagation of Viscoelastic Waves", Report (MX) 10/59, Ministry of Supply A. R. D. E. (May, 1959). B-4-45

A theory is discussed in conjunction with experimental evidence. A preliminary analysis of Kolsky's experimental results concerning the propagation of dilation waves is given. The possibility is discussed of evaluating theoretically the profiles of pulses propagating in viscoelastic solids, using Kelvin's stationary-phase approximation.

White, M. P., and Griffis, LeVan, "The Permanent Strain in a Uniform Bar Due to Longitudinal Impact", Journal of Applied Mechanics, Transactions ASME, 69, A-337-343 (1947). B-4-46

A method is presented for giving the final distribution of strains in a uniform bar subjected to a plastic impact. The wave propagation theories are used in the development. The presentation is very basic from the standpoint of interpretation of impact stresses and strain in cylindrical specimens.

Koehler, James S., and Seitz, Frederick, "On the Propagation of the Plastic Deformation Produced by an Expanding Cylinder", Armor and Ordnance Report No. A-139, National Defense Research Committee (January 26, 1943); ATI 25215. B-4-47

In this paper it is assumed, in accord with Bethe's model for armor penetration, that the plastic deformation produced during armor penetration is similar to that produced by an expanding cylinder. In the first portion of the paper, the relations between the stresses and the strains are considered, and the wave equations which govern the motion of the material when it is rapidly deformed are derived. It is found that in the case of the thick plate, an elastic wave diverges radially from the expanding cylinder, that this is followed by a plastic wave, and that the elastic and plastic wave velocities do not differ very much. In the second portion of the paper, an approximate expression

for the displacement is obtained for the case where the deformation is elastic. In the last section of the paper, a method of numerically integrating the wave equations is given.

Kumar, S., and Davids, N., "Basic Theory of Scabbing-Elasto-Plastic Wave Propagation", Interim Technical Report No. 10, Pennsylvania State University, Office of Ordnance Research, Project TB2-0001 (1253), Contract No. DA-36-061-ORD-465. B-4-48

Semi-graphical approaches to the propagation of stress pulses in bars created by impacts is presented. This report consists of two main parts, viz., "Stress Jump Approach" and the "Strain Contour Approach". In the first part, after a brief discussion and development of the theory of plastic wave propagation, solutions of a number of problems with various boundary conditions for rectangular and triangular pulses of both long and short duration, are presented. An idealized stress-strain diagram for 14ST-4 aluminum alloy has been used for most of the above cases. In the second part, the theory of contour propagation in the X-T plane is developed and a set of rules that govern their geometrical patterns are presented. Solutions are provided for most cases of reflections and interactions of the strain and velocity contours that are considered necessary for solving any given problem.

Kumar, Sudhir, "Scabbing and Pulse Propagation in Materials", Pennsylvania State University, Office of Ordnance Research, Project No. TB 2-0001 (1253), Contract No. DA-36-061-ORD-465 (August 1, 1958); AD 206768. B-4-49

A new method called the "Strain Contour Method" has been developed. By this method, a pressure pulse of arbitrary shape can be taken into account without breaking it into small rectangles. It also provides a detailed description of interaction of various wave fronts. In the development of the analysis various fracture criteria and scab lengths obtained in plates and bars under similar conditions were studied comparatively.

Lee, E. H., "A Boundary Value Problem in the Theory of Plastic Wave Propagation", Quarterly of Applied Mathematics, 10 (4), 335-346 (1952-1953). B-4-50

The theory of the propagation of plastic waves in one dimension is a case in which the solution, including the determination of the unknown plastic-elastic boundaries, can be treated. An example is presented in this paper which illustrates the many types of boundary-determination conditions which must be used. The method is based on the numerical integration along the characteristics of the hyperbolic equations arising, one linear and one quasi-linear. The development is possible since forward integration along characteristics enables the unknown boundaries to be determined independently of the subsequent solution. This situation is contrasted with other problems in the theory of plasticity. The complexity of the procedure indicates the difficulty to be anticipated with analytical treatment of such problems, and with the numerical treatment of problems involving more extensive plastic flow.

Lee, E. H., and Wolf, H., "Plastic Wave Propagation Effects in High Speed Testing", Office of Naval Research, Contract No. N7orn-353 (April, 1950); ATI 86902. B-4-51

This paper deals with the effect of high-speed testing on the plastic-wave propagation effect. A variation of strain occurs along the test specimen, and the stress-strain relation cannot be determined from measurements. If average values are taken, it is shown that a spurious strain-rate influence will be deduced when propagation effects first begin to appear as the testing speed is increased. It is important to eliminate this influence when determining the effect of strain-rate. The theoretical plastic wave analysis of a particular test arrangement is given. The range of speed is determined which permits satisfactory interpretation without the need for detailed analysis. Application to other test arrangements is discussed, and it is pointed out that a theoretical analysis can be made to predict the permissible speed range in planning a high-speed testing program.

Lee, E. H., and Kanter, I., "Wave Propagation in Finite Rods of Visco-Elastic Material", Journal of Applied Physics, 24 (9), 1115 (September, 1953). B-4-52

The paper deals with the propagation of pulses of one-dimensional, extensional waves in a linear Maxwell solid, which can be represented in the form of a model by a spring and a dash pot in series. The cases of an infinite rod and a finite rod are presented. The main features of the phenomena are determined by the relative magnitudes of relaxation time, t, and by the time for the elastic wave to transverse the length of the specimen.

Lensky, V. S., "The Construction of a Dynamical Tension-Compression Diagram Based on the Wave Propagation Theory", Proceedings of the Conference on the Properties of Materials at High Rates of Strain, Institution Mechanical Engineers (April-May, 1957). B-4-53

The proposed method of building the diagram is based on the fact that the strains of various magnitudes propagate at different velocities. The method does not work for high-elastic materials such as rubber. A method for the construction of diagrams for these materials is given.

Lunz, Y. L., "On the Propagation of Spherical Waves in an Elasto-Plastic Medium", Prikladnaia Matematika i. Mekhanika, 13 (1), 55-78 (January, February, 1949). In Russian. B-4-54

In this paper the propagation of spherical waves is being considered. This includes waves which are originating in a limitless space filled with elastic-plastic medium with applications of a centrally-symmetrical load on the surface of a spherical-carved hollow in this space. A case of active load is discussed and deformations are given of a displacement in an elastically- and plastically-deformed section of a sphere. The radii of the propagation of a strong break of a plastic wave is determined as a function of the magnitude of the original pressure. The method of construction of an approximate solution is offered for the region of deformation.

Mallory, H. D., "Propagation of Shock Waves in Aluminum", Journal of Applied Physics, 26 (5), 555-559 (May, 1955). B-4-55

The velocity of shock waves in aluminum and the associated translational motions, produced by metal-metal impact, have been determined by an electrical-contact technique. The results obtained have been used to evaluate an equation of state for the metal.

Malvern, L. E., "The Propagation of Longitudinal Waves of Plastic Deformation in a Bar of Material Exhibiting a Strain-Rate Effect", Office of Naval Research, Contract N7onr-358 (August, 1949); ATI 208632. B-4-56

This report extends the theory of propagation of longitudinal waves of plastic deformation to apply to materials in which the stress is a function of the instantaneous plastic strain and strain rate. Examples are given of the solution of the system of partial differential equations governing the motion. The solutions obtained indicate that the type of strain-rate dependency considered can account for the discrepancies in the stress-time variation at the fixed end of a tensile-impact specimen between the experiment and the previous theory, based on the quasi-static stress-strain relation. The strain-rate effect causes increments of stress to be propagated at a somewhat higher speed than was predicted by the previous theory.

Malvern, L. E., "The Propagation of Longitudinal Waves of Plastic Deformation in a Bar of Material Exhibiting a Strain-Rate Effect", Journal of Applied Mechanics, Transactions ASME, 73, 203-208 (January, 1951); Journal of Applied Mechanics, 73, 438-429 (December, 1951). B-4-57

The theory of propagation of plastic-longitudinal waves is extended to include the strain-rate effect on the stress-strain curve.

Malvern, L. E., "Plastic Wave Propagation in a Bar of Material Exhibiting a Strain Rate Effect", Quarterly of Applied Mathematics, 8 (4), 405-411 (1950-1951). B-4-58

A mathematical analysis is derived for the propagation of a transient wave of plastic deformation due to longitudinal impact on a bar which takes into account the high-strain rates occurring. The analysis extends the theory of other investigators to apply to materials in which the stress is a function of instantaneous plastic strain and strain rate.

Mikowitz, J., "On the Use of Approximate Theories of an Elastic Rod in Problems of Longitudinal Impact", Proceedings Third U. S. National Congress of Applied Mechanics, Brown University (June 11-14, 1958), ASME, New York (1958), p 215. B-4-59

Approximate solutions for the longitudinal-impact and pressure-shock problems in a semi-infinite circular rod, valid for long times, are derived in accord with the

Mindlin-Hermann theory. The solutions are shown to be equivalent. Further, they are in basic agreement with that of Skalak (Journal of Applied Mechanics, 79, 59 [195]) derived for the longitudinal impact problem from the linear equations of elasticity.

Comparison of radial and axial strains with experiment is made and good agreement is found, particularly in the case of axial strain. Over-all properties considered the Mindlin-Hermann offers the best approximate theories.

Miklowitz, J., "The Initiation and Propagation of the Plastic Zone in a Tension Bar of Mild Steel Under Eccentric Loading", Journal of Applied Mechanics, ASME Transactions, 69, A-21-A-30 (March, 1947). B-4-60

The author presents the results of several tests with flat tension bars of mild steel under eccentric loading. Attention is centered about the wedge-shaped plastic zones that form under this type of loading. A theory is formulated describing how the first wedges form and later cause additional wedges to form. Other tests are listed for comparison in which the load was applied centrally. The article is well-illustrated with sketches and photographs.

Paca, F. B., "The Response of Materials to Dynamic Loads", Technical Report 1643-TR, U. S. Army Corps of Engineers, Research and Development Laboratory (July, 1960). B-4-61

A review of the static and dynamic response of materials to stress is given. The action of stress and strain waves involved during impact is discussed in terms of wave propagation under various boundary conditions. Dynamic-load test apparatus is reviewed.

Pack, D. C., Evans, W. M., and James, H. J., "The Propagation of Shock Waves in Steel and Lead", Proceedings of the Physical Society, London, 60 (Part I), 1-8 (January, 1948). B-4-62

An experimental investigation is presented in which transit times for the passage of a shock wave through plates are measured. The wave is instigated by the detonation of an explosive. Lead and steel plates are used. Time is measured by making and breaking electrical contacts.

Plass, H. J., Jr., "Current Research on Plastic Wave Propagations at the University of Texas, Part I; A Theory of Longitudinal Plastic Waves in Rods of Strain-Rate Dependent Material, Including the Effects of Lateral Inertia and Shear", Proceedings Second Symposium Naval Structural Mechanics (1960). B-4-63

A mathematical theory is presented for the propagation of plastic-stress waves in long metal rods of strain-rate dependent material. The effects of inertia associated with radial motion and of radial shear associated with uneven changes in radius are taken into account.

Pytel, A., and Davids, N., "Further Transient Analysis of Stress Wave Propagation in Plates", Proceedings Fourth Midwest Conference Solid Mechanics, Austin, Texas, September, 1959, University Press, p 258-381. B-4-64

The effect of suddenly applied force gives rise to jump discontinuities in the displacement-time relation. Waves caused by the termination of the rectangular pulse cause reversed stresses of magnitude comparable to those produced by loading waves. For a unit-step pulse, the displacements due to incident and reflected waves are in the same direction.

Ripperger, E. A., "Current Research on Plastic Wave Propagation at The University of Texas, Part II. Experimental Studies of Plastic Wave Propagation in Bars", Proceedings Second Symposium Naval Structural Mechanics (1960). B-4-65

The results of a number of different experiments involving plastic-wave propagation are presented and discussed briefly. Some comparisons with theoretical predictions based on the theory presented in Part I are available for comparison.

Rubin, R. J., "Propagation of Longitudinal Deformation Waves in a Prestressed Rod of Material Exhibiting a Strain-Rate Effect", Journal of Applied Physics, 25 (4), 528-536 (April, 1954). B-4-66

This article considers the longitudinal propagation of stresses above the yield stress in a material exhibiting a strain-rate effect. The system consists of a semi-infinite rod subjected to end impact. If the rod is prestressed above the yield point and if the impact stress is not too large, the equations of motion are linear. Integral representations of the solutions can be obtained by the method of Laplace transformations. It is shown in general that the strain-rate solutions approach asymptotically the solutions obtained by von Karman and Taylor in a treatment which neglects the strain-rate effect. The propagation of the unloading wave is considered for the case in which the initial wave is a shock wave. The condition which defines the regions in the x-t plane, where the loading and unloading equations apply, is given. It is shown that an unloading shock wave will be absorbed except for the case of a material which does not work harden. In this case the complete solution of the unloading problem is obtained.

Sachs, R. G., "Some Properties of Very Intense Shock Waves", Physical Review, 69 (9-10), 514-522 (May 1 and 15, 1946). B-4-67

Conditions have been obtained for the existence of a steady shock wave of such an intensity that radiation pressure plays a role in determining the properties of the shock. These conditions are completely analogous to the Rankin-Hugoniot equations for ordinary shocks; they are obtained by consideration of the conservation of mass, momentum, and energy. The results are applied to hydrogen and to the very light gases. The application to other media requires high pressures and temperatures. In the light gases, the thickness of the shock front is extremely large because the radiation-free path, which is determined by Compton scattering, is very large. The velocity of sound in a medium under very high pressures and temperatures is also discussed, and it is found that this

velocity continues to increase with increasing pressure, a condition that is necessary for the shock to be stable.

Savitt, J., "A Note on Shock Propagation in Brass", Journal of Applied Physics, 24 (10), 1335 (1953). B-4-68

A theoretical description is given of the propagation of longitudinal waves through a body of large lateral extent (Plates). The combination of elastic and plastic stresses is investigated.

Savitt, Jacob, Stresau, R. H., and Starr, L. E., "Compression Wave Velocity Experiments with Copper", Journal of Applied Physics, 25 (10), 1307-1311 (October, 1954). B-4-69

A method for obtaining experimental compression-wave velocities in metals is described. Measurements of the compression-wave velocity in copper were made and found to be in good agreement with theoretical predictions. It is suggested that the discrepancy between the velocity (4730 meters per second) reported herein and that reported by Rinehart and Pearson (3600 meters per second) is associated with the different geometries of the two sets of experiments.

Schirmer, H., "On Bending Waves in Rods", Ingenieur-Archiv., 20 (4), 247-257 (1952). In German. B-4-70

Consideration of the propagation of flextural waves due to shock is given. Elementary-transverse and torsional waves with the effects of shearing force and rotational inertia are analyzed. Velocities and frequencies of the flexural sine wave, the propagation of the flexural shock, and the form of the wave at high frequencies are determined.

Selberg, Henrik L., "Transient Compression Waves from Spherical and Cylindrical Cavities", Arkiv for Fysik, 5 (7), 97-108 (1952). B-4-71

This paper deals with the transient compression wave emanating from a spherical or cylindrical cavity to the surrounding isotropic-elastic solid. It is supposed that the pressure at the boundary surface of the cavity is the same all over, depending only on the time. This supposition, however, only agreed with real circumstances if both cavity and charge are spheres with the ignition point for a centre. This is a consequence of the fact that the velocity of sound in the solid is not negligible compared with the velocity of detonation of the charge.

Smith, E. A. L., "Impact and Longitudinal Wave Transmission", ASME Journal, 77 (7), 963 (August, 1955). B-4-72

The article presents a numerical method for the approximate solution of problems such as action of a railroad train in propagation of an impact and the resulting longitudinal-wave transmission. Tables and curves of coefficients are given and lengthy

discussions by two other authors are included. The treatment of the subject is reasonably complete for the simple practical situations.

Sokolovskii, V. V., "Propagation of Elastic Viscous Plastic Waves in Bars", Prikladnaia Matematika i Mekhanika, 12 (3), 261-280 (1948). In Russian. B-4-73

This article reports the results of a research problem on the propagation of waves in bars of material which possess some elastic and some viscous-plastic qualities. These qualities of material are explained by some relations between strains and deformations described in differential form.

Stanyukevich, K. P., Unsteady Motion by Continuous Media, Pergamon Press (1960). Translation from Russian (Chapter VIII); AD 246577. B-4-74

This book deals with the mathematics of plane-detonation waves and the scattering of detonation products. The development of the theory is along classical lines for the propagation of a shock wave. In general the math is beyond the useful range of the high-energy-rate practictioner and should only be used where high-level experimental research in this field is to be conducted.

Sternglass, E. J., and Stuart, D. A., "An Experimental Study of the Propagation of Transient Longitudinal Deformations in Elastoplastic Media", Journal of Applied Mechanics, Transactions ASME, 20 (3), 427-434 (September, 1953). B-4-75

An experimental study is presented which is concerned with confirming the theory of the propagation of plastic waves. It is concluded that the velocity of propagation of the wave front is that of the elastic wave. This is not in agreement with theory as proposed by Von Karman and Taylor.

Tupper, S. J., "On the Propagation of Plane Stress Waves Generated in a Thick Steel Plate by a Surface Explosion", Armament Research and Development Establishment, Great Brittain (September, 1961); AD 269492. B-4-76

A discussion is presented concerning the propagation of plane stress waves through a steel plate finite in thickness but otherwise unlimited in extent, following the detonation of a uniform slab of explosive in intimate contact with one face of the plate. The problem is considered in two parts: the first relates to that case in which reflected waves from the rear of the plate are not considered; the second relates to a plate of definite thickness, and an endeavor is made to consider the interaction between forward moving and reflected-stress fronts. The solutions seek to start from a knowledge of basic physical properties of the explosive, the plate, and the geometry, together with a sufficiently accurate equation of state of the products of explosion and of the constitutive equation of the steel under the relevant physical conditions, and to derive the stress and particle velocity throughout the steel plate at all times.

White, M. P., and Griffis, LeVan, "The Propagation of Plasticity in Uniaxial Compression", Journal of Applied Mechanics, 15 (3), 256-260 (September, 1948). B-4-77

In a three-page article the author treats his subject by impact from various velocities, starting from lowest velocities in which the behavior in compression is similar to that found in tension to velocities higher than that of the speed of the elastic waves in which the material behaves like a fluid. This is a theoretical investigation and has several curves, sketches, and formulae to help treat the subject.

Cross References.

A-2-0-4 Shows that rate of shock-wave application from direct conversion of electrical energy is greater at source than for an explosive charge.

B-0-1 Deals with shock-wave propagation in solids.

B-2-2 Presents an idealized theory of cavitation in liquids. The boundary of the cavitated region either advances at supersonic velocity, or remains stationary, or recedes as a closing front.

B-3-2 Gives theory of spherical wave propagation in solids.

B-3-4 Discusses nonlinear waves in solids.

B-3-6 Analyzes shock-wave propagation in metals. Treats metals as fluids when compressions are high, thus giving solutions to many problems related to condensed detonation.

B-3-7 Describes shock waves in polyethylene and rubber.

B-3-8 Analyzes stress wave caused by longitudinal impact at the end of a cylindrical bar.

B-3-9 Gives method of computing velocity of plastic deformation.

B-3-10 Describes a new method for determining Hugoniet equation by using oblique shock measurements.

B-3-11 Investigates the behavior of an infinite plate of finite thickness having one face subjected to a plane pressure pulse.

B-3-12 Covers the classical theory of stress waves in solids, how this theory has been extended to cover non-perfectly elastic solids, and summarizes recent experimental work.

C-2-6 References to reports on propagation of shock waves.

E-2-10 Describes a new reflected-light measuring technique using oblique shock waves.

E-2-22 Studies form and intensity of stress distributions set up in a [illegible] t subjected to a shock wave.

E-2-27 Presents the effect of plastic-wave propagation on high-[illegible] sting.

E-2-30 Compares the properties of plastic and elastic waves in [illegible]

F-1-0-59 Analyzes the velocity of strain propagation, covering [illegible] udinal as well as transverse waves.

H-9-1 Discusses effect of oblique impact of a cylinder on [illegible] a target.

J-3-2 Shows that negative pressures (necessary for [illegible] r-stress cutting) occur where two rarification waves meet.

J-3-8 Analyzes stress propagation by graphical met[illegible] od.

K-1-9 Gives experimental technique of magnifying stre[illegible] by transmitting the impact through steel rods of two cross-section cha[illegible] ges.

K-1-20 Describes method for determining yield strength of [illegible] el at a very high strain rate.

K-1-34 Presents pressure-resistance method for measuring st[illegible] and a photo-cell method for measuring strain.

K-1-54 Describes behavior of metal subjected to a shock wave ba[illegible] d on the dynamic properties of the metal.

K-1-67 Gives detailed description of apparatus used to measure no[illegible] uniform yield under dynamic straining.

[illegible]-2-7 Calculates pressure profiles in steel under explosive loading.

K-2-[illegible] Describes metallographic technique for determining the level of [illegible] ssure to which iron plates have been subjected by explosive loading.

## Facility Requirements

Location C-1

Hall, Clarence, and Howell, Spencer P., "Magazines and Thaw Houses for Explosives", Technical Paper No. 18, United States Bureau of Mines (1912). [illegible]-1-1

The general requirements for magazines are given. Plans for and metho[illegible] f construction are listed. The basic problem in the storage of explosives is their [illegible] fe-keeping from unauthorized access. A secondary requirement is to prevent the d[illegible] terioration of the explosive.

"Explosive Forming Seen Cutting Tool Costs for Spacecraft Parts", American Metal Market, 14 (September 25, 1961). C-1-2

Some of the work being conducted at General Dynamics/Astronautics is discussed. Their new facility is comprised of two buildings, a five-ton hoist, and two explosive magazines in a 16,000 square-foot area. Cost of the facility was $40,000.

The new facility's 12-foot diameter tank can be used to form missile parts up to 8 feet in diameter and 6 feet in height.

Cross References.

F-1-0-99 Discusses types and locations of explosive-forming facilities.

F-3-0-7 Discusses Dynapak and its development.

## Facility Requirements

### Construction C-2

Close, Gilbert C., "Facts About Explosive Metal Forming", Modern Machine Shop, 108-113 (May, 1959). C-2-1

Research work conducted by Aerojet-General Corporation indicates a brilliant future for a new process in space age production. A list of facilities at Aerojet and the general background of explosive forming are given.

"Explosive Forming Tested by Rocketdyne", Steel, 145 (26), 74-75 (December 28, 1959). C-2-2

This article shows a series of photographs of work being performed and facilities used. Conclusions reached are that:
cost of facility is less than machinery to do same job,
thick stock forms better than thin,
springback and welds can be a problem in titanium,
part size is not a problem, and
metal sandwiches can be formed without destroying the core.

"Explosive Forming Scores at General Dynamics", Steel, 149 (15), 145 (October 9, 1961). C-2-3

The article describes facilities for explosive forming at General Dynamics Corporation. Their new layout includes a 12-foot water tank, two buildings, a 5-ton hoist, and two explosive magazines in a 16,000 square-foot area.

Keil, A. G., "Problems of Plasticity in Naval Structures: Explosive and Impact Loading", Proceedings Second Symposium Naval Structural Mechanics (1960). C-2-4

The emphasis of the paper is on the problems associated with explosive and impact loads. Loads from underwater explosives are discussed, as are typical naval problems having to do with impact loads. The problems of the stiffened panel and the ring-stiffened cylindrical shell are given as examples.

Zernow, Louis, "Applications of High Velocity Metal Forming (HVMF) in Short Run Production", ASTME Paper No. SP 62-67, presented at the Creative Manufacturing Seminars (1961-1962). C-2-5

Information is given on the various possible energy sources for high velocity metal forming. A discussion of the economics of each is given. A more detailed discussion of the economic and technical aspects of explosive metal forming is given including discussions of die-design problems and safety problems. The personnel and facility requirements are discussed and analyzed.

"Protective Construction", Astia Report Bibliography AD 242653, Armed Services Technical Information Agency, Arlington, Virginia (November, 1960). C-2-6

Entries in the bibliography include references to reports pertaining to characteristics of nuclear explosions, propagation of shock waves, underground explosions, soil mechanics, and response of structures to blast. References are limited to unclassified reports without specific distribution limitations. Literature coverage is restricted to documents within the Armed Services Technical Information Agency's collection, cataloged from 1952 to September 15, 1960.

<u>Cross References.</u>

| | |
|---|---|
| B-1-5 | Presents a series of experiments carried out using small charges of high explosives detonated centrally in closed cubical steel boxes. |
| B-1-7 | Gives results of air blast damage tests using the following explosives: Torpex 2, H-C, Tritonal, Comp B, Pentolite, and TNT. |
| C-1-1 | Presents plans and methods of construction of magazines. |
| C-1-2 | Describes new facilities for explosive forming. |
| F-3-0-3 | Gives particular attention to construction of equipment. |

## Facility Requirements

### Operation C-3

Franken, Peter A., "Preliminary Survey of High-Speed Impact Information", WADC Technical Report 58-577 (June, 1959); AD 216029. C-3-1

This report summarizes studies of high-speed impact now under way. Experimental facilities for obtaining high velocities are considered, and advantages and disadvantages associated with the various propulsion systems are discussed. A separate classified title lists capabilities of existing propulsion systems. Methods of analyzing high-speed impact-data are reviewed.

Range Clearance, Standing Operating Procedures, Ohio Military District, OMD Camp Perry 4076H, 4 (April 9, 1954). C-3-2

This SOP covers the control of the firing range at Camp Perry, Ohio. The procedures and methods of control of the area during operations are given and can be used as reference material in establishing the safety of an explosive forming facility.

Cross References.

C-1-1 Discusses the basic problems in the storage of explosives.

C-2-5 Discusses various possible energy sources for high energy rate forming and the economics of each.

F-1-0-89 Describes operation of explosive forming facility at Ryan.

F-3-0-3 Gives particular attention to operation of equipment.

## Tooling Requirements

### Die Materials D-1

Back, P. A. A., and Campbell, J. D., "The Behavior of a Reinforced Plastic Material Under Dynamic Compression", Proceedings of the Conference on the Properties of Materials at High Rates of Strain, Institution Mechanical Engineers (April-May, 1957). D-1-1

The theory of a method of test which is similar to that of Kolsky is developed. Results are given for two resin materials. The results are discussed with particular reference to their implications as to the modes of failure under slow and rapid loading.

Bryan, B. I., "Epoxy Dies for Explosive Forming", The Tool Engineer, 44 (1), 97-102 (February, 1960). D-1-2

This article covers the advantages of using epoxy dies for explosive forming. The reduction of pressures as they pass through water and the part being formed permits the use of epoxy. The time required to make an epoxy die is considerably less than for a kirksite or steel die and in most cases the closer tolerances obtainable with a steel die are not warranted. The cast-face type die is the least desirable for explosive forming while the laminate-face and solid epoxy are considered best. A glass-cloth reinforcement is the most desirable; however, both quartz and metal cloth have been considered. The techniques used in the construction of epoxy dies follows closely the techniques used in fabrication of conventional plastic tooling.

Korol, V. K., and Perlin, I. L., "Deformation Resistance of the Alloy TsAM9-1, 5 in the Temperature Range of Hot Deformation by Compression", Izerestiya Vysshikh Uchebnykh Zavedemii Tsvetnaya Metallurgiya (5), 159 (1959). In Russian. D-1-3

Deformation by tension, wire drawing, and compression at various temperatures is discussed. The influences of rate and degree of deformation and temperature on the stress causing deformation are presented.

The material investigated (TsAM-1,5) is similar to kirksite and has the following composition: Pb, 0.03; Sn, 0.01; Zn balance; Cu, 1.0-2.0; Si, Mg 0.03-0.06; Mn, 0.10; Fe, 0.20; Cd, 0.02; Al, 8.0-11.0; impurities 0.50.

Salter, R. J., "Epoxide Dies for Explosive Forming of Sheet Metal", British Plastics, 34 (3), 116 (March, 1961). D-1-4

The author presents the advantages of using epoxide dies rather than Kirksite or ductile iron. The greatest advantage is the smaller amount of time required to construct the die. He mentions several types of epoxide dies - the cast-face, laminated-face, and solid-resin dies. Ryan Aeronautical Company has used these dies to form nose cones for DC-8's.

"Hottest New Die Materials for Explosive Forming", Machine and Tool Blue Book, 57 (Issue No. 9), 102-105 (September, 1962). D-1-5

The article covers work being conducted at Aerojet-General Corporation using ice dies in explosive forming. Some of the critical aspects of fabrication of the ice dies are listed: the water solution, the physical structure of the ice that is formed, the porosity of the ice, the freezing time of solution, the impurities in the solution, and the nature of the heat-transfer medium. All of these are considered to be critical for the successful preparation of an ice die. The article contends that the ice dies can be produced at one fourth the cost required for the production of an all-metal die for an explosive-forming operation. Operations with high explosives are limited on ice dies to concentric parts.

Cross References.

A-2-0-3 Describes tooling development of the electro-hydraulic process of high-energy-rate forming.

F-1-0-10 Outlines materials required for tooling in high explosive forming.

F-1-0-13 Mentions some materials used for dies in explosive forming.

F-1-0-66 Discusses various types of dies and the stresses they are subjected to.

F-1-1-23 Covers the concept of ice dies for explosive forming.

F-1-8-1 Recommends materials to use in a die for high-energy forming of titanium.

F-1-8-5 Mentions use of ductile iron castings for explosive forming dies.

F-3-7-1 Discusses useful die material for extrusion with a Dynapak.

## Tooling Requirements

### Die Design D-2

Philipchuk, Vasil, "Dieless High Energy Rate Forming and Production Parts for H. E. R. F.", ASTME Report No. SP 60-162, presented at the Creative Manufacturing Seminars (1960-1961). D-2-1

Dieless forming has applications where the percentage of deformation required to form the part is not great. A great advantage of dieless forming is the cost of the operation. Die costs are a good portion of the total costs in a die-forming operation, varying up to 75 per cent depending on part size and quantity required. Dieless operations will fall into two categories (1) bulged cylinders, and (2) dish-shaped parts.

The answer to the question of when parts should be made by high-energy techniques can be set down as when parts require stricter tolerances, larger tools, or numerous fabrication operations per part when made by conventional techniques. Stamping or press operations as well as automatic-machine forming should be left to the conventional forming techniques.

#### Cross References.

C-2-5 Discusses die design problems in explosive forming.

D-1-2 Covers the design of epoxy dies.

F-1-0-10 Presents an outline of die design for high explosive forming.

F-1-0-18 Discusses design considerations for explosive forming dies.

F-1-0-95 Mentions one specific die design for explosive forming.

F-1-1-10 Covers the development of explosive forming of contoured aluminum skins for missile nose cone applications and the use of cast steel dies.

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| F-1-1-12 | Discusses forming over a lead plug as well as an air cushion system and free forming processes. |
| F-1-1-19 | Discusses new developments in dies at Ryan. |
| F-1-6-6 | Demonstrates feasibility of explosive forming domes of a desired contour with special tooling techniques. |
| F-1-8-1 | Describes a possible die design for explosive forming titanium alloys. |
| F-3-0-10 | Covers the selection of tooling for pneumatic-mechanical equipment. |
| F-3-7-1 | Discusses useful die designs for extrusion with a Dynapak. |
| K-1-76 | Discusses the design of tooling for explosive forming at room and elevated temperatures. |

## Tooling Requirements

### Die Construction D-3

Penning, F. A., "Response of a Free-Standing or Anchored Explosive Forming Assembly", ASME Paper No. 62-WA-108, Presented at the Winter Annual Meeting of the American Society of Mechanical Engineers, New York, November 25-30, 1962. To be published January, 1963. D-3-1

This investigation considers an explosive-forming assembly where an elastic base is able to take compressive loads but cannot support tension. The release of the compression without restraint may result in an undesirable rebound of the assembly. Height of the rebound is found for three different pressure-pulse shapes: rectangular, triangular, and exponential. Length and area of anchoring bolts to restrain an assembly may be determined for a given bolt material. Also included are explosive-property curves for TNT and water.

#### Cross References.

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| D-1-2 | Gives techniques for the construction of epoxy dies. |
| D-2-1 | Discusses dieless forming where only a small percentage of deformation is required to form the part. |
| F-1-0-10 | Outlines construction of tooling for high-explosive forming. |
| F-1-1-20 | Gives information on the construction of dies for explosive forming of large parts. |
| F-1-8-1 | Describes construction of a die for high-explosive forming of titanium alloys. |

## Equipment Requirements

### Water Tanks E-1

"Bubble Tank Cuts Costs at Explosive Forming Plant", Steel, 147 (19), 120 (November 7, 1960). E-1-1

A curtain of compressed air bubbles inside the walls of the forming tank cuts pressure from an underwater explosion five to six times. The source of the bubble curtain is an aerator, a simple doughnut of 3-1/2-inch pipe placed near the bottom of the tank. Holes are drilled on 2-inch centers. Air pressure is regulated to admit 300 cubic feet a minute. This system has permitted operations of a tank with 0.5-inch-thick steel walls above ground level for explosive-forming operations. The tank is 13 feet in diameter, and 13 feet deep.

#### Cross References.

F-1-0-58 Discusses advantages of explosive forming in a water pit.

F-1-8-6 Describes water-pit installation for explosive forming.

## Equipment Requirements

### Measuring Devices E-2

Bell, J. F., "Normal Incidence in the Determination of Large Strain Through the Use of Diffraction Gratings", Proceedings Third U. S. National Congress of Applied Mechanics, Brown University (June 11-14, 1958), ASME, New York (1958), p 489. E-2-1

In this paper the advantage of using normal incident light is discussed for the measurement of large strain by means of diffraction gratings. Exact expressions for both strain and surface angle are obtained and a direct method of over-all calibration is discussed, this latter permitting considerable improvement in accuracy over that previously reported for the method. Results are given for a 30,700 lines per inch, 0.010-inch-long diffraction-grating gage on a specimen undergoing dynamic plastic strain from a constant-velocity impact.

Betser, A. A., and Frocht, M. M., "A Photoelastic Study of Maximum Tensile Stresses in Simply Supported Short Beams Under Central Transverse Impact", Journal of Applied Mechanics, 24 (4), 509-514 (December, 1957) and 25 (2), 305-306 (June, 1958). E-2-2

Photoelastic-streak photographs were taken for beams subjected to the impact of a heavy mass. Experimental techniques are not fully discussed.

Bron, W. E., Zadwick, K. A., and Tarr, A. L., "New Method for Recording Explosion Impulse Effects on Solids", ASTM Bulletin No. 220, 50-51 (February, 1957). E-2-3

The article describes a method of measuring properties of elastic waves as propagated in metals and generated by explosives or other means, using strain gages, amplifiers, and an oscilloscope for recording. The method proved to be useful in experimenting with brittle failures.

Caldwell, Frank R., and Fiok, Ernest F., "Some Factors Influencing the Performance of Diaphragm Indicators of Explosion Pressures", U. S. Bureau of Standards Journal of Research, 26 (3), 175-196 (March, 1941). E-2-4

Information is presented which was obtained during the development and use of accurate diaphragm-type indicators of the pressures developed during explosions of gaseous mixtures in bombs. Although some of the following conclusions are not original, all are supported by new experimental evidence. It is shown that all passages and cavities on the explosion side of the diaphragm should be eliminated for highest accuracy. Although the sensitivity of the diaphragm to pressure difference must not be less than the value determined by the accuracy with which pressures are to be measured, it is important when highest accuracy is desired, that the sensitivity shall not greatly exceed this same value so that the inertia error will not become larger than the allowable tolerance. Radial tension in the diaphragm is advantageous in reducing time lag. A blued or polished surface is preferable to one which absorbs more radiant energy. Projections around the diaphragms are without measurable effect upon the performance of the indicators. It seems probable that, with a properly designed indicator, the measured values of explosion pressure need not deviate from the actual pressure by more than a few tenths of one millimeter of mercury.

Clark, D. S., and Duwez, P. E., "Discussion of the Forces Acting in Tension Impact Tests of Metal", Journal of Applied Mechanics, Transactions ASME, 15 (3), 243-247 (September, 1948). E-2-5

A method is described for measuring the forces acting on a specimen during a tension-impact test. Plastic wave propagation theory is used to interpret the results obtained. Impact velocities to a maximum of 200 feet per second are considered. The interpretation of force-time curves obtained from such tests are discussed thoroughly.

Conrad, R. W., and Vigness, I., "Response Spectra by Means of Oscillograph Galvanometers", Journal of the Acoustical Society of America, 29 (10), 1110-1115 (October, 1957). E-2-6

A response spectrum (shock spectrum) is the response of a series of a single-degree-of-freedom systems of given damping to a shock or vibratory motion, as a function of the frequencies of the simple systems. An oscillographic galvanometer is a single-degree-of-freedom system having a rotational response to an exciting current. If the exciting current is made proportional to the amplitude of the motion, the response of the galvanometer to the current will be proportional to that of a single-degree-of-freedom system to the motion, provided their natural frequencies and damping properties

are the same. A commercial galvanometer-type oscillograph has been obtained having twelve undamped-galvanometer elements with natural frequencies in the range between 10 and 2500 cps. Damping by electrical means has been made adjustable between 3 and 50 per cent of critical. Associated circuitry have been constructed so that electrical playback of recordings of shock and vibratory motions can be conveniently analyzed. Calibration techniques are described and examples are given for analysis of simple and complex shock motions.

Courtney-Pratt, J. S., "A New Photographic Method for Studying Fast Transient Phenomena", Proceedings of Royal Society of London, 204, Series A (1076), 27-33 (November, 1950). E-2-7

A system is described which makes use of the features of the image-converter tube combined with a time-base-deflexion system similar to any that could be used in a cathode-ray oscillograph. By avoiding entirely the use of mechanically moving parts the method is free of the inherent limitations of writing speed of all the earlier instruments. Vibration is eliminated and this, too, in general, results in better definition and resolution. Wide-aperture lenses can be used without difficulty, and the over-all intensity compares favorably with that of the best mechanical cameras.

Crook, A. W., "A Study of Some Impacts Between Metal Bodies by a Piezo-Electric Method", Proceedings of the Royal Society, Series A, 212 (1110), 377-390 (May 7, 1952). E-2-8

Continuous measurements of the force throughout impacts between metal cylinders and between a hard sphere and metal flats are described. The force has been measured piezoelectrically. Within their appropriate ranges the theories of elastic impacts due to St. Venant and Hertz have been confirmed. For impacts so hard that the elastic regime preceding plastic deformation may be neglected, it is shown that the experimental results agree closely with force-time curves calculated, assuming that deformation is opposed by a constant pressure. This dynamic-flow pressure is greater than the similarly defined pressure experienced in static tests and the new information given by the piezoelectric method shows that this difference cannot be accounted for satisfactorily in terms of forces of a viscous type. (Physics Abstracts, 1952)

Dimoff, John, "A Survey of New Developments in Pressure Measuring Techniques in the NACA", Ames Aeronautical Laboratory, Moffett Field, California, National Advisory Committee for Aeronautics, Presentation at London, England (March 24-28, 1958). E-2-9

Presentation covers various types of transducers used to obtain measurements on aerodynamic models. The dynamic-capacitance-cell transducers have particular applications to high-energy-rate measurements. The frequency response of such a desired transducer is beyond 200 kilocycles. The device operates by measuring the change in capacitance due to the compression of a thin layer of dielectric material which is subjected to an unknown pressure.

Doran, D. G., Fowles, G. R., and Peterson, G. A., "Shock-Wave Compression of Aluminum", Physical Review Letters, 1 (11), 402-404 (December, 1958). E-2-10

A new reflected-light technique with oblique-shock waves allows dynamic-pressure-compression measurements to be made in the region between existing dynamic measurements (50-500kbar) and the elastic regime. The advantages of this technique over argon gaps are given.

Durelli, A. J., and Dally, J. W., "Some Properties of Stresscoat under Dynamic Loading", Proceedings of the Society for Experimental Stress Analysis, 15 (1), 43-56 (1957). E-2-11

This paper deals with a systematic study which was conducted to determine the influence of the manufacturer's coating number, coating thickness, and curing temperature on both the dynamic- and the static-strain sensitivities of the brittle coating known commercially as Stresscoat. The dynamic-strain sensitivity was determined by using a hollow tapered-wall cylinder as the calibration member which was loaded by a falling tub arrangement. The static-strain sensitivity was determined by using the conventional cantilever-calibration fixture. A comparison between the dynamic- and static-strain sensitivities showed that, in general, the dynamic strain required to crack the coating was higher than the static strain.

Edgerton, H. E., "Shock Wave Photography Improved", Industrial Laboratories, 9 (7), 6-8 (July, 1958). E-2-12

The article describes Edgerton's method of taking shock-wave photos under bright-light conditions. It describes the screen material behind the subject as Minnesota Mining and Manufacturing Scotchlite type 244 and Black type 234. The flash tube used for the exposure was an FX21 Xenon-filled Vycor tube developed by Edgerton's own company. Pictures and tables are included for blasting-caps and rifle-shot subjects. A possible method of taking large scale photos of a full scale aircraft flying at high speed is suggested.

Elliott, K. W. T., and Wilson, D. C., "An Optical Probe for Accurately Measuring Displacements of a Reflecting Surface", Journal of Scientific Instruments, 34, 349-352 (September, 1957). E-2-13

The probe described is capable of accurately measuring the displacement of a plane reflecting surface along its normal axis without making mechanical contact with it. The image of an illuminated grating of special construction is formed on the surface to be observed, and the light reflected from this surface then forms an image of equal size on a second, exactly similar, grating. The disposition of the second image relative to the second grating depends upon the position of the probe relative to the plane surface.

Displacements may be measured with a standard deviation of $2.8 \times 10^{-5}$ inches. The device is apparently for static deflections but appears to have promise for dynamic conditions.

Fanning, R., and Bassett, W. V., "Measurement of Impact Strains by a Carbon-Strip Extensometer", Journal of Applied Mechanics, Transactions ASME, 7 (1), A-24-A-28 (March, 1940). E-2-14

This paper describes a method of experimentally ascertaining the actual stress-time curve in a mechanical part subjected to an impact blow. The apparatus consists of a resistance strain gage in conjunction with a high-speed recording oscillograph, the combination being sufficiently rapid in response to record strain variations occurring within a few microseconds. Consequently, the strains during impact are recorded with sufficient accuracy for detailed analysis.

Fink, Kurt, "Experimental Determination of the Yield Point of Mild Steel Under Impact Loading (Die experimentelle Bestimmung des Fliessbeginns von Flusstahlen bei schlagartiger Beanspruchung), Archiv fur das Eisenhuttenwesen, 19 (473), 153-160 (1948). In German. E-2-15

Experimental techniques for determining dynamic-yield strength of materials which have been subjected to both tensile and compressive waves are described.

Fitzgibbon, D. P., "Stress-Strain Characteristics of Materials at High Strain Rate, Part I", Structural Mechanics Research Laboratory, The University of Texas. E-2-16

A photoelectric method for measuring displacements during high-velocity impacts is described. The theory of the system is discussed in detail and a prototype system which was built and tested is described. The performance of the prototype system is evaluated by comparing the results which it gives with results obtained by other methods of measurement. The system was found capable of a resolution of at least 0.01 inch.

Fowler, C. M., Minshall, Stanley F., and Zukas, E. G., "A Metallurgical Method for Simplifying the Determination of Hugoniot Curves for Iron Alloys in the Two-Wave Region", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), p 275-308. E-2-17

Equation of state data are presented for iron alloyed with nickel and/or chromium, and a technique is explained which utilizes metallurgical examination of recovered specimens to facilitate the determination of the Hugoniot curve in the two-wave region of these alloys. An error analysis is presented and indicates that data obtained by this technique should be reliable to within a few per cent.

Gallup, Rolland, and Pearson, John, "The Use of High Speed Stereophotography to Study Explosive Metal Forming", ASTME Report No. SP 62-06 presented at the Creative Manufacturing Seminars (1961-1962). E-2-18

This paper describes a method for using medium-speed and high-speed stereophotography to obtain quantitative engineering data in connection with explosive-forming

operations. The analysis of the data is readily performed since the method utilizes commercially available instruments and techniques such as those used for the contour plotting of maps from aerial photographs. Details of the method are described in conjunction with a preliminary study of the free forming of a thin aluminum plate by means of a small charge of high explosive.

Gibson, F. C., Summers, C. R., and Scott, F. H., "Studies on Deflagration to Detonation in Propellants and Explosives", ARP Order No. 44-61, U. S. Department of the Interior, Bureau of Mines, Pittsburgh, Pennsylvania (October 30, 1961); AD 266743. E-2-19

Some of the various new laboratory techniques which can be used for the measurement of deflagration and detonation of explosive mixtures are discussed. An optical technique for sensing behavior within an opaque body is under development and appears promising for use in combustion-rate studies when correlated with the results of resistance-element and pressure-probe techniques.

The influence of externally applied electric and magnetic fields on detonation had been discussed in earlier reports.

Habib, E. T., "A Method of Making High-Speed Compression Tests on Small Copper Cylinders", Journal of Applied Mechanics, Transactions ASME, 15 (3), 248-255 (September, 1948) and 16 (1), 98 (March, 1949). E-2-20

High-speed-compression tests were performed on small copper cylinders by subjecting them to the impact of a piston fired from a pneumatic gun. Experimental techniques are discussed and results of the tests are shown as energy absorbed versus deformation. The complication due to plastic-strain waves is mentioned.

The velocity of impact was from 25 to 200 fps.

Hopkinson, Bertram, "A Method of Measuring the Pressure Produced in the Detonation of High Explosives or by the Impact of Bullets", Philosophical Transactions of the Royal Society of London, Series A, 213, 437-456 (February, 1914). E-2-21

The direct determination of a force acting for a few hundred-thousandths of a second presents difficulties which may perhaps be called insuperable, but the measurement of the other factor, the duration of the blow, is more feasible. In the case of impacts such as those of spheres or rods moving at moderate velocities the time of contact can be determined electrically with considerable accuracy. The present paper contains an account of a method of analyzing experimentally more violent blows and of measuring their duration and the pressures developed.

Jahn, R. G., "Photoelastic Stress Analysis of a Shock Loaded Structure", Paper presented at meeting of the Division of Fluid Dynamics, American Physical Society, Ithaca, New York, September 11-12, 1951, Princeton University Department of Physics Technical Report II-9, Contract NR061-020, N60Ri-105. Abstract from Physical Review, 84 (3), 612 (November 1, 1951). E-2-22

To study the form and intensity of the stress distributions set up inside an object subjected to a shock wave, a solid model of photoelastic Bakelite was mounted in the shock tube and the stress progressions in it were analyzed by means of a conventional circular polariscope. Patterns were taken at 10 to 20 microsecond intervals starting at the time of impact.

Kirby, P. L., "Apparatus for the Measurement of Time of Impact", British Journal of Applied Physics, 7, 227-228 (June, 1956). E-2-23

An apparatus is described for measuring the time of impact of a ball impacting on a plane surface. A direct connection to the ball is not necessary. The plane surface forms one surface of a capacitor. The other capacitor electrode is a ring at about 5 mm above the plane surface. The ball drops through the ring which changes the capacitance. While the ball is in contact with the surface, the capacitance is unchanged and therefore a measure of the time of impact.

Kolsky, H., "An Investigation of the Mechanical Properties of Materials at Very High Rates of Loading", Physical Society of London Proceedings, 62 (Section B), 676-700 (1949). E-2-24

A method of determining the stress-strain relation of materials when stresses are applied for times of the order of 20 microseconds is described. The apparatus employed was a modification of the Hopkinson pressure bar, and detonators were used to produce large transient stresses. Thin specimens of rubbers, plastics and metals were investigated and the compressions produced were as high as 20 per cent with the softer materials. It was found that while Perspex recovered almost as soon as the stress was removed, rubbers and polythene showed delayed recovery, and copper and lead showed irrecoverable flow. The phenomenon of delayed recovery is discussed in terms of the theory of mechanical relaxation and memory effects in the material.

Konoenko, V. G., "Impact Testing Machine for High-Speed Test of Materials", Zavodskaya Laboratoriya, 25 (3), 343-346 (1959). E-2-25

Rapid tests are possible for elongation, compression, bend, and diverse metal treatments at varying rates of deformation and temperature ranges with this machine. A description of the machine's operational characteristics is presented with possible uses for the equipment.

Krafft, J. M., "Instrumentation for High-Speed Strain Measurement", Response of Metals to High Velocity Deformation Conference, Estes Park, Colorado, July 11-12, 1960; Interscience Publishers, New York (1961), p 9-49. E-2-26

In many materials, important strain rate effects can be observed by recording load and head displacement at increased head speed. Success in such an endeavor requires: (1) that strain be uniformly distributed along the specimen, (2) that the testing machine have adequate speed input and stiffness characteristics, and (3) that load and head position during the rapid test be accurately measured. The instruments described solve these problems. Desirable characteristics of bonded-wire strain gages and the connecting circuitry are noted. Difficulties of resistance strain gaging in dynamic tests include magnetostrictive effects and adherence to the specimen of epoxy-resin-based foil gages.

Lee, E. H., and Wolf, H., "Plastic-Wave Propagation Effects in High-Speed Testing", Journal of Applied Mechanics, ASME Transactions, 73, 379-386 (December, 1951). E-2-27

The problems involved in testing materials at increasing speeds are presented. A method of testing is used consisting of an anvil on which the specimen is placed and a piston which is driven against the specimen at a controlled velocity. Sketches, curves, and formulae are used to illustrate the author's approach to the subject. Several sizes of hollow and solid pistons are used and the results are presented in the form of curves.

MacDonald, R. J., Carlson, R. L., and Lankford, W. T., "Apparatus for Determination of Stress-Strain Properties at High Rates of Strain", Proceedings Society for Experimental Stress Analysis, 14 (1), 163-170 (1956). E-2-28

This article describes a machine used for tensile testing up to a strain rate of 190 inches per minute. Load measurements are made with a dynamometer made from electric strain gages (SR-4). Head travel is controlled hydraulically. Strain of the specimen is measured with a clip-gage extensometer placed between the loading heads.

Mallory, H. D., "On the Existence of a Binary Reaction Zone at a Metal Explosive Boundary During Detonation", U. S. Naval Ordnance Laboratory (1954), PB 122054. E-2-29

This report is a summary of recent progress made in the interpretation of pin-point data. The pin technique has been used to measure the free-surface velocity of an aluminum target struck by a plane-detonation wave from crystalline TNT at a loading density of 0.624 g/cc.

Minshall, Stanley, "Properties of Elastic and Plastic Waves Determined by Pin Contactors and Crystals", Journal of Applied Physics, 26 (4), 463-469 (1955). E-2-30

Experimental techniques are described by which one can observe the separation of a shock wave in a metal into an elastic wave and a slower plastic wave. The plastic-wave velocity was about 15 per cent less in steel and 10 per cent less in tungsten than the elastic-wave velocity, at pressures imparted by Composition B explosive. Elastic-wave velocities were the same, within experimental error, as the measured sound

velocities. The pressure in the elastic wave in SAE 1020 steel, deduced from the material and wave velocities, is independent of the plastic-wave pressure, within experimental accuracy, and is about 12 kilobars. SAE 1040 steel, however, does not exhibit a single characteristic elastic-wave pressure. The pressure initially is about 6 kilobars, and increases to about 12 kilobars before the arrival of the plastic wave.

Mintrop, H., "Measurements of Large Impact Forces", Schweizer Archiv fur Angewandte Wissenschaft und Technik, Zurich, 16 (4), 119-124 (1950). E-2-31

The author's method of measurement of impact forces is based on Hertz classical equations concerning the contact between elastic-solid bodies. In order to verify their validity and utility for this purpose, extensive static and dynamic tests were made, where the contact areas between spheres and plane-solid surfaces were measured and the corresponding forces observed and computed. Balls were dropped on plane surfaces, and new methods, one of them involving the use of high-speed films, were used to measure the time of impact and the diameter of the circular contact surface.

Papirno, R., and Gerard, G., "Dynamic Deflection Transducer Utilizing Photoconductive Sensors", Review of Scientific Instruments, 26 (10), 968-969 (October, 1955). E-2-32

A deflection transducer for dynamic studies in which the movable element has negligible inertia is described. The sensing element utilizes a light-beam incident upon a photoconductive cell which is modulated by a suitably-gridded film strip attached to the specimen at the desired location. The output of the photoconductive-cell circuit is a varying-voltage signal applied directly to a cathode-ray oscilloscope. A calibration scheme is described and the results of tests are given. The data indicate agreement within 2 per cent over the entire calibrated range of deflections.

Pearson, John, and Rinehart, John S., "Application of the Engravement Method to the Study of Particle Velocity Distribution in Explosively Loaded Cylinders", Journal of Applied Physics, 26 (12), 1431-1435 (December, 1955). E-2-33

A description is given of the application of the engravement method to the study of particle-velocity distribution in the wall of a thick-walled metal cylinder internally loaded with an explosive charge. Tests were conducted with this method on modified cylinders of annealed low-carbon steel and brass. Even though each of the modified cylinders broke into a number of fragments, the engravements were well enough preserved to furnish considerable data. Many measurements were obtained from each cylinder by using a large number of pellets of several thicknesses. Particle velocity data were obtained to within 7/16 inch from the metal-explosive interface. Temporal-particle-velocity distribution curves are presented for each of the cylinders.

Rinehard, J. S., and Pearson, J., "Engravement of Transient Stress Wave Particle Velocities", Journal of Applied Physics, 24 (4), 462-469 (April, 1953). E-2-34

Quantitative information on the high-intensity transient waves set up by impulsive loading is usually required in order to design rationally against failure under such loads. To obtain reliable data is often difficult when the loads last only a few microseconds and reach magnitudes of several hundred thousand pounds per square inch. A technique is described which enables quantitative determinations to be made either of particle velocity within the transient wave or velocity of propagation of the wave. The scheme consists of measuring the depth of the permanent impression or engravement that is left on a surface when a pellet that has been previously affixed to that surface flies off. The engravement is a direct consequence of the impingement of a transient wave against the surface. Considerable numerical data are presented which establish the validity of the scheme. The simplicity of the technique suggests that it may find extensive application in impulsive investigations.

Riparbelli, C., Hitch, H., and Boehler, G., "Photoelastic Stress Analysis of a Shock Loaded Structure", Paper presented at Meeting of the Division of Fluid Dynamics, American Physical Society, Ithaca, New York, September 11-12, 1951. Abstract in Physical Review, 84 (3), 614 (November 1, 1951). E-2-35

The analysis of stress propagation in solids of nonconstant section has occasioned the development of this technique, of which some of the first results are presented. High-velocity moving pictures (4000 frames per second) were taken in the polariscope of specimens made out of gelatin. The specimens were struck by a hammer at various velocities between zero and 30 feet per second. Moving pictures of isochromatic patterns are presented with emphasis on the boundary effects in plates of various shapes.

Romine, H. E., "Study of a Ballistic Method for Determining the Dynamic Yield Strength of Metals and Its Application to Titanium Alloys", Proceedings of the Symposium on Materials Research in the Navy, Philadelphia, Pennsylvania, March 17-19, 1959, ONR-S, 2, p 532. E-2-36

Improvements on the test described in 1948 by G. I. Taylor and A. C. Whiffin are discussed. Briefly, the method consists of firing a cylindrical specimen of the material under investigation from a smooth-bore gun against a rigid flat target, measuring directly the impact velocity and deformation of the cylinder.

Seitz, Frederick, Jr., Lawson, Andrew W., and Miller, Park, "The Plastic Properties of Metals at High Rates of Strain", Report No. A-41, National Defense Research Committee (April 8, 1942); ATI 25153. E-2-37

A machine constructed for the determination of the plastic properties of metals at high strain rates is described. It is operated at present as a compression-test device and will be used to study armor steel and other metals, such as the copper used for pressure measurements. It is pointed out that the difficulties which accompany compression testing are easier to overcome than those accompanying tensile testing, and that the relative advantages of compression testing are many. Preliminary results for copper crusher cylinders and for armor steel are described. The results for the copper cylinders indicate that a maximum speed effect of about 15 per cent is encountered in the range in which the cylinders are ordinarily used.

Suits, Dr. C. G., "Notes on High Intensity Sound Waves", General Electric Review, 39 (9), 430-434 (September, 1936). E-2-38

This article contains information on photographic methods of determining velocity of propagation of sound waves, the investigation of spark impulses, the operation of a continuous record rotating mirror camera, the extinction of discharges by sound waves, and the sound energy produced by sparks.

Tangerman, E. J., "Shock Simulator Shows Promise", American Machinist, 100 (9), 124-125 (April 23, 1956). E-2-39

Based on a familiar principle of physics, an arrangement of piston and cylinder shows possibilities as a shock tester and as a press for high-velocity, high-impact forming of aluminum, titanium, and some steel alloys. The device described provides a high-level controllable thrust-time curve, and can be tandemed or paralleled and self-triggered. The article covers early work Convair-San Diego performed in the development of their Dynapack machine.

Taylor, W., and Morris, G., "The Absolute Measurement of the Available Energy of High Explosives by the Ballistic Mortar", Transactions of the Faraday Society, 28, 545-558 (1932). E-2-40

The ballistic mortar permits the strength of an explosive to be expressed in absolute units. The theory of the mortar is simply that of an internal-combustion engine, or of a gun with the provision that the whole of the explosive is converted into its decomposition products before any appreciable mechanical work has been performed. If the charge is made too small, or the loading density too great, the losses become much more serious, and quantitative expressions for their variation have been given in the paper. The mortar in its most modern form is an instrument of considerable precision, as is shown by the very low value obtained for the standard deviation of results obtained over a long period, but it must be operated with care and with a full knowledge of the variations to which it is subjected, otherwise it may yield misleading results.

Vigness, I., "Measurement of Shock", Mechanics Division, U. S. Naval Research Laboratory (1960). E-2-41

A description of shock measuring instruments and a discussion of their limitations is given. The limitations must be known in order to attach proper significance to the measurements. If a simple equivalent to the shock motion cannot be found, the shock motion is expressed in terms of its shock spectra.

"Piezoelectric Ceramic Materials", Final Report SC-4203 (TR), Sandia Corporation, Albuquerque, New Mexico (January-February, 1958). E-2-42

This report describes characteristics of piezoelectric crystals for use in measuring peak pressures and energy of an explosive.

"Detonation and Explosive Phenomena", Progress Report No. 6, U. S. Department of the Interior, Pittsburgh, Army Project 599-01-004; ORD Project TB2-0001; AD 56893. E-2-43

This report covers photographic techniques for detonation waves and results of a study of parameters of the detonation process.

Hegge, E. N., and McDonough, J. P., "Watertown Arsenal Light-Gas Gun", Technical Report No. Wal TR 761/64, Watertown Arsenal Laboratories (December, 1960). E-2-44

A simple, practical, low-cost light-gas gun has been developed by the Watertown Arsenal Laboratories to conduct terminal-ballistic studies in the velocity range of 6000 to 13,000 feet per second. Standard cartridge cases and propellant are used to propel a lightweight plastic piston to compress the light gas (helium). The light gas is shaped to flow uniformly behind the projectile through the launching tube or rifled barrel by a disposable cone of plastic material which also serves as a buffer to decelerate the piston without appreciable damage to any major structural component. Either full-caliber conventional shear-type projectiles or subcaliber projectiles, fragments, and other irregularly shaped missiles can be fired, the latter by means of plastic-discarding-carrier techniques, in either smoothbored launching tubes or rifled barrels. Firing rates up to 20 rounds per day are easily attained.

Cross References.

A-1-1-21 Describes measurement of spherical structure using photographs from multispark camera, streak camera, condenser-microphone, Kerr-cell photography, and X-ray photography.

A-1-1-32 Gives techniques for measuring physical properties at detonation. Some of these properties are velocity of detonation, temperature, density changes, and Chapman-Jouguent pressure for explosives.

A-2-2-4 Shows graphs of voltage and current versus time for various wire sizes.

B-4-9 Describes use of diffraction gratings of very short length to study propagated plastic wave fronts.

B-4-10 Describes use of diffraction gratings to determine dynamic plastic strain.

F-1-2-3 Describes use of diaphragm pressure gage.

F-1-6-3 Describes bulge-test methods.

G-1-2-2 Describes methods and equipment for measuring high-velocity impact.

## Equipment Requirements

### Miscellaneous E-3

Mikhalopov, G. S., "Direct Explosion of Welded Joints", Welding Journal, Welding Research Supplement, 29, 109-s-122-s (March, 1950). E-3-1

The article describes a new technique for determining triaxial sensitivity of steel plates and weldments. A presentation is given of results using various combinations of electrodes and low-alloy steels. The article suggests the use of direct-contact high explosives as a means of checking the triaxial ductility of material since the stress wave generated is triaxial in nature. An undesirable feature of this type of test is the speed with which the stress is applied.

Ultra High Pressure Apparatus, Engineering Supervision Company, New York. E-3-2

Various types of equipment which have been developed by this company are described in this brochure. The equipment presented is believed to be useful in the following research areas: (1) improvement of physical properties of metals and other materials, (2) development of new metallic and new chemical compounds that can be produced by the application of ultra-high pressures, and (3) phase transformation and the densification of powders.

"Development of High Loading Rate Testing Machine", Final Report, Hesse-Eastern, Flightex Fabrics, Inc., Everett, Massachusetts, Contract No. DA-19-020-501-ORD-5164 (September 11, 1961); AD 267947. E-3-3

This report covers the design, development, and testing of a high-loading-rate tensile-test machine. Capacity of the machine is 15,000 pounds. A hydraulic loading cylinder is linked to the specimen and is pressurized with nitrogen gas on one side of the piston, and hydraulic fluid on the other side. Loading is applied rapidly by venting fluid out of the liquid end of the cylinder. Two gas-pressure-storage reservoirs and a system of electric valves and timers allow a programming of the loading pattern to include pulsed and stepped loads. An electrically operated loading valve allows variation of loading rate with rise times from one second to 20 milliseconds. Faster loading rates with rise times less than 5 milliseconds are obtained by using a pressure-operated rupturing shear disc as the loading valve.

"Forming", Steel, 146 (1), 280-285 (January 4, 1960). E-3-4

Fenwal's new explosion-protection system is described. The detector notes the ignition of an explosive, and within the few milliseconds between ignition and the explosion itself, it actuates a suppressing device which (1) smothers the explosion, (2) vents the pressure into the atmosphere, (3) uses suppressant to prevent explosion spread, (4) isolates explosion from adjacent areas, or (5) shuts down equipment.

Cross References.

A-1-1-31 Describes equipment and explains its functions.

A-1-1-36 Discusses use of line generators as part of plane wave technique.

K-1-17 Gives design and construction of a special rapid load testing machine.

K-3-21 Shows use of high-speed photography for measuring stress fluctuation in beams caused by the impact of a hammer.

K-3-40 Mentions adaption of Taft-Pierce Shock Machine with Electronic Devices for measuring dynamic loading of a low-carbon steel.

## Forming

Wood, W. W., Goforth, R. E., Ford, R. A., et al., "Theoretical Formability Volume I Development", and "Theoretical Formability Volume II Application", ASD TR 61-191 (I and II), Chance Vought Corporation for USAF, ASD, on Contract No. AF 33(616)-6951, Project No. 7387 (August, 1961). F-0-0-1

This report establishes equations for determination of the formability of materials analytically from the physical properties of the materials. A subsequent contract will establish equations for the determination of formability by high-energy-rate techniques.

"Mechanik der Spanlosen Formung" ("Mechanics of Chipless Forming"), Zeitschrift des Vereines Deutscher Ingenieure, 76 (3), 49-54 (January, 1932). F-0-0-2

The theoretical mechanics of hot- and cold-forming operations are discussed. Graphs of experimental data are compared with the theoretically-derived values for metal-forming operations of extrusion, bending, and deep drawing.

Bennett, K. W., "Lightning Strikes Powerful Blow", Iron Age, 186 (16), 121-122 (October 20, 1960). F-0-0-3

This article discusses briefly all three methods of high-energy-rate forming - electrospark, explosive, and pneumatic-mechanical - but it puts more emphasis on the electrospark method. The author also mentions the work being done in Russia with electrospark energy sources.

"Forming", Steel, 146 (1), 280-285 (January 4, 1960). F-0-0-4

A series of short discussions by leading men in the forming industry is presented. Most of these articles concern new developments in the industry with special emphasis on the high-energy-rate forming methods.

"High Energy Processes Shape Space-Age Parts" (Based on secretary's report by C. W. Gipe, Ryan Aero. Co.), Society of Automotive Engineers Journal, 69 (3), 44-45 (March, 1961). F-0-0-5

This article describes the three main high-energy forming methods - electrical, high-energy impact, and explosive. It gives a good listing of the requirements and capabilities of each of these methods as well as materials which can be formed.

Ottestad, J. B., "Looking Ahead the Next Ten Years in Manufacturing by the High Energy Rate Plastic Deformation of Materials", Society of Automotive Engineers, Preprint No. 52-T (1959). F-0-0-6

The author begins with a basic discussion of what happens when metal is worked and why high-energy-rate metalworking alleviates one of the difficulties. Next, he gives a brief state-of-the-art survey. Finally, he offers some predictions, based on the above two discussions, of what will be done in the metals fabrication industry in the next ten years.

Rosenthal, Paul, and McAdams, H. T., "A General Study of Processes for the Realization of Design Configurations in Materials", Project NEOS/Interim Technical Progress Report No. NM-1559-P-1 (ASD-IR-1), October, 1961, Cornell Aeronautical Laboratory, Buffalo, New York, Contract No. AF 33(600)-42921, Project NR 7-867; AD 267212. F-0-0-7

A rationale and a systematic approach were developed from a novel, completely generalized abstract concept of the manufacturing process. Processes are classified according to form of energy, mode of energy transfer, environment, and process topology. Materials are classified according to type of bond; the dominant role of their structure-sensitive properties is discussed. Exploratory studies of phenomena suitable for novel processes are presented; e.g., a recently discovered mechanical-resonance phenomenon shows promise of reducing the required flow stress in certain forming operations.

Wood, W., "Application and Limitations of High Energy Rate Forming Processes", Report No. 2-22300/2R-18, Chance Vought Corporation, Dallas, Texas (August 22, 1962). F-0-0-8

The report deals with the development of analytical method to predict limiting sizes of the most elliptical part shapes for the newer high-energy-rate-forming processes. Principal applications are defined based on part shape, part size, and available energy of the forming process. Deformation-work equations are developed for the most eliptical part shapes based on true stress, true strain, and the volume of material undergoing deformation.

Experimental parts were formed to determine the efficiencies of forming various parts by the high-energy-rate processes. Optimum efficiencies were determined based on the forming parameters of each process and localized thinning of the part.

Cross References.

A-1-0-8 Discusses the development of scaling laws for explosive forming operations.

F-1-0-59 Analyzes velocity of strain propagation, covering longitudinal as well as transverse waves caused by forming.

## Forming

### Chemical System F-1-0

Baker, W. E., and Allen, F. J., "The Response of Elastic Spherical Shells to Spherically Symmetric Internal Blast Loading", Proceedings of the Third U. S. National Congress of Applied Mechanics, Brown University, June 11-14, 1958, ASME, New York (1958), p 79. F-1-0-1

A general theory of the small-deformation elastic response of spherical shells of any thickness to spherically-symmetric internal-blast waves is developed. The theory is approximated for thin shells, and compared with experiment.

Baker, W. E., "The Elastic-Plastic Response of Thin Spherical Shells in Internal Blast Loading", Journal of Applied Mechanics, 27 (Series E), 139 (March, 1960). F-1-0-2

Using the theory developed for the title problem linear analytic solutions are obtained with small-deflection equations of motion for shell materials which exhibit various degrees of strain hardening. Numerical solutions are also presented for the equations for large deflections obtained by accounting for shell thinning and increase in radius during deformation. The theory is shown to be in good agreement with experimental results.

Beltran, A. A., "High-Impact Metal Forming (1957-1960)", Lockheed Aircraft Corporation (July, 1960); AD 241995. F-1-0-3

This bibliography is primarily concerned with articles on explosive forming; however, articles on electro-discharge machining, impact extruding, and shooting of bolts into metals have been included. The bibliography was compiled by Lockheed Aircraft Corporation during the performance of an Air Force contract on explosive forming.

Von Bezard, A., "Les Resultats Recents des Recherches Faites par la Societe Du Pont de Nemours sur le Formage, le Soudage et le Durciessement des Metaus par Explosifs", Rev de Metallurgie, 58 (11), 939-950 (November, 1961). F-1-0-4

Results of recent investigations by du Pont de Nemours in Switzerland concerning explosive forming, welding, hardening of metals, and compacting of metal powders is given. A summary of techniques employed and typical examples are presented.

Cole, D. W., "Explosives Press-Form Difficult Shapes", American Machinist, 102 (87), 137-139 (April 21, 1958). F-1-0-5

Virtually every operation possible at a drop-hammer press, brake, or stretch press has been duplicated by explosive forming. This includes stretching, bending, shearing, piercing, embossing, inlaying, and joining.

Cook, J. H., "Working Metals by Detonating Explosives", Sheet Metal Industries (London), 396 (37), 253-258 (April, 1960). F-1-0-6

The author discusses forming or shaping metals by detonating explosives; welding, compacting metal powders, engraving on metals, hardening metals, cutting metal plates, and boring holes in metals are discussed.

Cook, J. H., "Engraving on Metal Plates by Means of Explosives", Research (London), 1 (Supplement 10), p 474 (July 1947-1948). F-1-0-7

The article deals with the engraving of a design onto a metal surface using a stencil and explosive charge.

Cooley, R. A., "Theory and Practice of Explosive Metal Forming", American Machinist, 103 (12), 128-130 (June 15, 1959). F-1-0-8

EMF, explosive metals forming, is a new and not yet exact science that forms metal to die shape by explosive impact. The explosive charge is a form of stored energy that can be released (detonated) to move the metal workpiece – sometimes into shapes that cannot be economically produced any other way. It has the function of a press operation, but it can exert higher pressure faster, and it is often less expensive. Fundamentally the system has four elements: (1) a metal blank to be formed or expanded, (2) an explosive charge, (3) a die – or perhaps no die because free forming is also possible, and (4) a medium (usually water) that will transmit the explosive energy.

Cox, Floyd A., "Ryan's Experience in Explosive Forming", Metal Progress, 80 (2), 71-73 (August, 1961). F-1-0-9

The article presents methods whereby Ryan has simplified the fabrication of complex shapes and produced close-tolerance parts using the explosive-forming process. Pictures are used to show examples of what can be done with explosive forming and to point out its potential to design engineers dealing with tough forming problems.

Cox, Floyd, "Explosive Forming - Research Thru Development to Production and Methods of Tooling", ASTME Report No. SP 62-03, presented at Creative Manufacturing Seminars (1961-62). F-1-0-10

This paper presents an outline of the technique, tooling, and know-how required to establish an explosive-forming operation in production. The limitations of the process as well as the benefits to be derived are presented. Examples of the various types of explosive-forming work which has been conducted at Ryan are given.

Dickinson, T. A., "Explosive Working - Forming and Machining by High-Energy Methods", Aircraft Production, 21 (10), 236-249 (October, 1959). F-1-0-11

A general discussion of the use of explosives for forging, shearing, extrusion, and blanking operations is given. Some work on hardening and machining as well as explosive welding is presented. Work being performed at Nitroform, Inc., Grumman, and Lockheed is discussed.

Dickinson, T. A., "Report on Explosive Forming", Light Metals, 22 (254), 136-137 (May, 1959). F-1-0-12

Conflicting opinions were frequently voiced by some 20 forming experts who served as panelists during more than two full days of special technical sessions at the Eleventh Western Metal Congress and Exposition, Los Angeles, in March. But they all agreed that high-energy-rate forming is here to stay.

Dickinson, Thomas A., "Underwater Forming of Metals", The Explosives Engineer, 37 (4) (July-August, 1959). F-1-0-13

This article gives a very brief description of the explosive-forming process. It mentions some of the materials which have been formed and some materials which have been used for dies.

Douglas, John J., Forming Practices With High Explosives, Technical Information on Du Pont Explosive Specialties, Wilmington, Delaware. F-1-0-14

The Du Pont Company's experience in the explosive forming of metals for commercial applications is reviewed and reference made to the fundamental studies conducted. Samples of pieces formed with various explosive charges ranging from a blasting cap to several pounds of high explosives are illustrated. The effects of charge shape, weight and standoff are discussed, and data are presented for charge determination and die design.

DuMond, T. C., "Forming Metals at High Velocities", Metal Progress, 74 (5), 68-76 (November, 1958). F-1-0-15

A survey of methods of "high-energy-rate" and "explosive" forming is presented. Because of low die and equipment costs, the methods are particularly valuable for parts

needed in limited quantities. Other advantages are elimination of springback and ability to handle extremely large parts.

Edwards, William, "High-Energy Forming", Welding and Metal Fabrication, 26 (4), 138-139 (April, 1958). F-1-0-16

The author gives a brief history of American explosive forming and gives pictures of trapped-fluid energy transfer, trapped rubber, piston transfer, and direct blast to form blanks.

Feddersen, E. W., "High Energy Rate – Its Application to Metal Forming", Journal of Metals, 12 (9), 682-686 (September, 1960). F-1-0-17

The applications of explosive forming, hydrospark forming and pneumatic-mechanical forming are discussed. Although the feasibility of these operations has been proven and various parts are being made on a production basis, the problem of hand finishing and handling of parts still causes a longer time for operations of fabrication than is required by more conventional fabrication methods. The tools and materials for tooling still leave much to be desired, although improvements are being found. It is believed that these difficulties will be overcome and that the use of this technique will eventually offer engineers vast design freedom.

Gorcey, R., Glyman, J., and Green, E., "Advanced Fabrication Techniques", Paper No. 61-AV-13, American Society of Mechanical Engineers (Dec. 22, 1960). F-1-0-18

This paper discusses three advanced fabrication techniques currently in use at Rocketdyne. These techniques are filament winding, explosive forming, and furnace brazing. Among the items discussed for each technique are the process advantages, applications, economics, and design considerations.

Goyer, Guy G., "Explosive Forming Studied in Quebec Laboratory", Canadian Machinery, 71 (3), 74-76 (March, 1960). F-1-0-19

An outline of the process – advantages, limitations, and explosive hazards – is presented.

Greenley, Robert E., and Bickley, William H., "Explosive Metal-working...Its Applications Status", PB 181067, U. S. Department of Commerce, Office of Technical Services (1962). F-1-0-20

A general review of explosive forming is presented with predictions of uses in the future. It is emphasized that a considerable amount of research is still required to provide practical processing information so that the technique may be used with a minimum amount of trial and error.

Hanley, Fiske, "High Energy Rate Forming at General Dynamics/Fort Worth", ASTME Report No. SP 62-15, Presented at Creative Manufacturing Seminars (1961-62). F-1-0-21

This paper provides a brief background and a descriptive explanation of the use of each high-energy source and its applications. A discussion of how they are put to use, their limitations, problems encountered, and potential applications for each are presented. Explosive, electric spark, electromagnetic, and pneumatic-mechanical energy sources are covered. Stainless steels, alloy steels and superalloys have been formed with this equipment.

Heilveil, Sidney, "High Energy Rate Forming from Development to Production", ASTME Report No. SP 60-177, presented at Creative Manufacturing Seminars (1960-61). F-1-0-22

A review of the various types of high-energy-rate forming operations which are being placed into production is given in this paper. It was concluded that high-energy-rate forming is still in its infancy but that it has demonstrated its capabilities and pointed out its potential. It was also noted that very little interest exists in the applications of high-energy techniques in the continental European trade journals. Russian scientific journals, on the other hand, have been displaying considerable interest.

Hodge, P. G., Jr., "The Influence of Blast Characteristics on the Final Deformation of Circular Cylindrical Shells", Journal of Applied Mechanics, 23 (4), 617-624 (December, 1956). F-1-0-23

The final maximum deformation of a reinforced-circular-cylindrical shell caused by a briefly-applied intense loading is considered. The maximum deformation is obtained in a form which requires a double quadrature of the pressure when the limits of the integration are determined from side conditions. Since a simple analytic approximation for loads of practical importance could not be found, a graphical-numerical method of solution is devised. Several examples are considered in support of the conclusions. The shell is assumed to be infinitely long, so that end effects may be neglected. The load is assumed to be applied to the entire shell simultaneously. The shell is assumed a perfect cylinder, and reinforcements are taken as rigid. Finally the shell is assumed to be made of an ideal rigid-plastic material which satisfies a certain simplified yield condition and the associated flow rule.

Philipchuk, Vasil, "Production Explosive Forming Techniques", ASTME Report No. SP 62-91, Presented at the Creative Manufacturing Seminars (1961-62). F-1-0-24

A general coverage of the factors involved in the selection of the explosive-forming process is presented. Methods of analysis for selection as well as determination of facilities' requirements and location are covered. Explosive costs are analyzed on the basis of inhouse-charge fabrication vs purchase of desired-charge configurations.

Lambert, P. F., "Explosive Forming Meets Space-Age Production Demands", Machinery, 65 (10), 124-128 (June, 1959). F-1-0-25

Methods, advantages, and limitations, current status, and future possibilities of explosive forming are discussed. The information presented is based on a recent cross-country survey of applications by the author.

Lessing, Lawrence, "Blasting Metals into Shape", Fortune, LXIV (3), 127-131 (September, 1961). F-1-0-26

A general description of the process is given with relationship to work which has been performed in the field by various companies. Photographs of some very large parts which have been made by high-energy-rate forming and description of some of the techniques used are given.

Lockwood, E. E., and Glyman, J., "The Explosive Formability of Metals", ASTME Report No. SP 62-09, presented at the Creative Manufacturing Seminars (1961-1962). F-1-0-27

This paper presents the results of research and development studies conducted at Rocketdyne. Both theoretical and experimental data are presented concerning the plastic deformation of a thin metal diaphragm subjected to underwater-explosive loading. Data is correlated by relating the explosive energy transported by the shock wave to the plastic work done on the diaphragm. In addition, data regarding observations of the explosively formed samples, formability relationships, and die considerations are presented.

McGuire, F. G., "New Approaches to Explosive Forming: Industry Putting Increased Emphasis on HEF Processes", Missiles and Rockets, 5 (14), 28-29 (April 6, 1959). F-1-0-28

A general discussion of explosive forming and of pneumatic-mechanical forming using a Dynapak machine is given.

Monteil, Vernon, "How to Design for Explosive Forming", Metal Progress, 80 (2) (August, 1961). F-1-0-29

To design for the use of explosive forming it is necessary to consider that the process is a supplement to conventional forming techniques, and is by no means a cure-all for forming problems. The process becomes attractive where parts are too large for conventional forming equipment, tolerances closer than those obtainable with conventional equipment are required, or where the number of parts required would prohibit the making of matched sets of dies for press operation. Often multiple operations can be performed by explosive forming where separate dies would be required to use conventional techniques. The process has the capability for forming both symmetrical and unsymmetrical details from material as light as foil and as heavy as heavy plate. The only material with which limited success has been obtained by forming with this process is beryllium.

Olofson, C. T., and Boulger, F. W., "Bibliography on Explosive Metal Working", DMIC Memorandum 51, Battelle Memorial Institute, Columbus (April 7, 1960). F-1-0-30

210 references are given. A short discussion of current research in explosive forming is presented.

Orr, James P., "Trends in High-Energy Forming of Metals", American Society of Mechanical Engineers Paper No. 62-MD-21 (March 9, 1962). F-1-0-31

This paper is a review of some of the important aspects of explosive forming, such as limitations and conditions for appropriate use, die configurations, and explosives and their application. Comments on the future of explosive forming in industry are presented.

Park, Ford, "High Energy Rate Metalworking", International Science and Technology, 1 (6), 12-23 (June, 1962). F-1-0-32

This article covers a recent survey of the work being performed in the high-energy-rate forming field. All of the high-energy-rate forming processes are discussed in terms of applications to production and areas of research and development. An interesting discussion of the dislocation theory and how it applies to high-velocity working of metals is given.

Pearson, John, "Metal Working with Explosives", Journal of Metals, 12 (9), 673-681 (September, 1960). F-1-0-33

A general review of present uses for explosives in metal working is presented. The types of energy sources used and specific data on their physical characteristics are given. Methods for determining peak pressure and impulse available from an explosive are given. The effect of the explosive-stress wave on materials is discussed. A study of the present state of high-energy-rate metalworking operations indicates that only forming operations have been placed in the production category. Other operations, such as metal powder compaction and explosive welding, are still in the research stage. It is indicated that the practical use of explosives in metalworking has been satisfactorily demonstrated but the limits of applications in various operations are yet to be established.

Pearson, John, "The Explosive Working of Metals", Paper presented at the Society of Aircraft and Materials Engineers Symposium, Dayton, Ohio (March 9-10, 1960); AD 238394. F-1-0-34

Various types of explosives are discussed briefly and some limits of pressures and times as related to the workpiece are given. A table of typical detonation rates is included, as well as velocities of elastic waves in materials. A series of formulas are developed to indicate how peak pressures at the workpiece may be varied as a function of charge size, standoff and two different transmittal media. Stress waves and some wave-velocity equations are discussed. Tables of stress particle data as well as critical impact velocities and associated normal fracture stresses are given for several metals. A wide variety of explosive-working operations is discussed (including the forming, sizing, and flanging of sheet metal stock and plate) which are normally standoff

operations. Other operations mentioned are controlled work hardening, forging, extruding, welding, controlled cutting, compacting, and forming of powders. These are usually contact operations.

The article concludes with a brief discussion of material behavior.

Philipchuk, Vasil, "Explosive Forging", AMC Final Technical Report 59-7-694, for USAF, AMC on Contract No. AF 33(600)-37751 (October, 1959). F-1-0-35

Explosives were proven feasible for producing close-tolerance one-sided closed-die aluminum-alloy forgings for aircraft and missiles. Capital investments for explosive forging are lower than for conventional forging but operating costs are higher.

Rardin, Glen N., "Shock Forming with Explosives", Metalworking Production, 101 (11), 448 (1957). F-1-0-36

This article deals with experiments performed at Lockheed by the author.

Rardin, Glen N., "Explosives Fabricate Metal at Lockheed", American Machinist, 101 (1), 112-115 (January 12, 1957). F-1-0-37

This article covers a three phase research program at Lockheed on explosive forming.

(1) Punching holes - stud driver is used to drive a piston through materials which cannot be drilled.

(2) Pressure forming with low explosives - forming of Types 347 and 4130 stainless tubes is done in female die with 8-gage shotgun shells as energy source.

(3) Pressure forming with high explosives (PETN & Primacord) - cup forming was chosen to investigate elongation work hardening and effect of shock-wave impact upon structure of metal.

Piper, F. C., Rardin, G. N., and Richter, W. L., "High Energy Rate Metal Forming", Final Technical Engineering Report (October 18, 1957 to August 1, 1960), AMC TR 60-7-588, Lockheed Aircraft Corporation, California, Contract No. AF 33 (600)-35543, AMC Project No. 7-588 (October, 1960). F-1-0-38

This paper discusses the high-energy-rate forming of sheet metal for airframe and spacecraft applications. The forming techniques developed demonstrate that the controlled application of the energy available from high velocity explosives is safe, efficient and economical. The inherent advantages, as well as the limitations of this new

forming method, are presented for consideration in the design of and for the production of "difficult to form" sheet metal components.

Rinehart, John S., "High Energy Rate Forming via Explosives", ASTME Report No. SP 60-138, presented at Creative Manufacturing Seminars (1960-61). F-1-0-39

This paper presents a general discussion of the use of high and low explosives in an explosive forming operation. It is stated that metals show considerably less ductility when formed by high-energy-rate techniques than they do when formed by conventional methods. This is providing the comparison is made at room temperature. Since limited data are available on strain-rate effects on the ductility of metals it is suggested that the mechanical properties of metals at low temperatures have many analogies, both behavior patterns being dependent upon activation energies in much the same way. It should be further noted that in none of the high-energy applications is the metal subjected to such pressures that it is converted to a fluid.

Rinehart, J. S., "Explosive Working of Metals", Mines Magazine, 50 (1), 31-33 (January, 1960). F-1-0-40

When explosives are placed in intimate contact with a metal and detonated, the stresses just inside the metal will instantaneously become exceedingly high and a transient stress disturbance is set up. This stress disturbance is transmitted through the metal, producing fracture, plastic flow, and other deformations, the exact nature of which will be strongly dependent on the configuration of the metal-explosive system.

Savitt, Jacob, "Explosives Form Tubes With and Without Dies", American Machinist, 103 (12), 135-137 (June 15, 1959). F-1-0-41

The use of explosive charges to expand tubing is described. Both the free forming and die forming of tubing details are covered. Primacord was used for most of the tubing experiments since the shape of the charge could be readily altered to meet specific requirements. Possible techniques for cutting and punching operations are considered. A steel ball between an explosive charge and the part to be blanked shapes the pressure wave to produce a high-pressure cutting jet.

Schroeder, William, "Tentative Analysis of Some Problems With Explosives", Report No. MAS 56, Lockheed Aircraft Corporation, Burbank, California (January 14, 1958). F-1-0-42

Within the range of rates of deformation investigated there is little or no evidence that there is greater ductility obtained as a direct result of high straining rates. Any apparent improvement in ductility is probably due to other causes such as high hydrostatic pressures that have occurred with the high straining or forming rate.

Within the range of experiments the yield strength tends to increase with the rate of straining. This suggests that dynamic stress-strain curves are possibly quite different from the near static ones commonly pictured.

It is necessary to consider not only the primary shock wave but also at least the first order reflections from the interface.

The success of an investigation of forming by means of high energy explosives will very probably depend in part upon the development of means of controlling the time pressure profiles of the pressure waves.

Simons, Charles C., "Explosive Metalworking", DMIC Memorandum 71, Battelle Memorial Institute, Columbus (November 3, 1960). F-1-0-43

This report is a compilation of data and a review of previous reports on explosive metalworking. Principal effects on metallurgical structure and applications of the process are covered up to the present time. Previous work on metal powder compaction, explosive welding and possible new applications are presented.

Stambler, Irwin, "Explosive Forming Breaks Fabrication Bottleneck", Space/Aeronautics, 30 (5), 50-55 (November, 1958). F-1-0-44

A presentation of Aerojet's Aeroform process (high-energy-rate forming) is presented. The thesis that work hardening is prevented and that springback is eliminated due to the elimination of surface stresses is advanced. This is believed to be due to the extreme speed of metal movement.

Tangerman, E. J., "Shock Forming With Explosives", American Machinist, 101 (1), 110-111 (January 14, 1957). F-1-0-45

A history of the use of explosives for metal forming is presented.

Tardif, H. P., "Techniques for Explosive Forming: Forming Cones by Metal Gathering", Metal Progress, 76 (3), 84-85 (September, 1959). F-1-0-46

Copper cones were explosively formed by recessing the blank into the die prior to forming rather than using a hold-down ring as is customary with drawing operations. Hardness and thickness measurements in the walls of the cones produced show that blanks respond in two ways to the forming pressure. In part of the cone, the wall thickness exceeds that of the original blank indicating that metal gathering has taken place. At the apex, deep drawing has made the wall thinner than the workpiece. The hardness of the zone of "zero deformation" (no apparent change in wall thickness) exceeds the original hardness of the blank. It was also found that, for the same amount of deformation, the change in hardness in the metal-gathering zone is much higher than in the area of deep-drawn metal.

Tardif, H. P., "High-Energy Rate Forming of Metals", CARDE Technical Memorandum No. 290/59 (August 3, 1959); AD 241982. F-1-0-47

A general review of a new metalforming technique commonly called explosive forming has been carried out in this paper. The main variables involved are briefly

described. The materials and shapes formed to date and the metallurgical and dimensional aspects are discussed. The theories as to why explosive forming works are mentioned. Other metalworking operations performed by means of explosive energy such as hardening, welding, the pressing of powders, etc., are reported. Finally, the use of explosive forming in the missile industry and the broad aspects of Canadian work in explosive metallurgy are reviewed.

Vlahos, Charles J., "Shaping Metal With Dynamite", Popular Science, 181 (5), 106-109 (November, 1962). F-1-0-48

A general discussion of the work being conducted in the United States on explosive forming, pneumatic-mechanical forming, and electric-discharge forming is given. Some of the work being conducted on explosive forming at The Martin Company, Denver, is discussed. Also mentioned is some of the magnetic forming work performed with equipment manufactured by the Electrodynamics Corporation. Some of the components which are being formed or joined on the magnoform-type equipment are discussed and shown in numerous photographs.

Vensel, Henry, "A Booming Business", Production, 80-83 (March, 1960). F-1-0-49

This article gives a general discussion of work being performed in the field of explosive forming, machining, and compacting of powders.

One section covers Republic Aviation's spark-bomb forming.

Wagner, H. J., and Sabroff, A. M., "History and Scope of High Energy Rate Forming", ASTME Report, presented at Creative Manufacturing Seminars (1960-1961). F-1-0-50

Subjects discussed include forming by means of explosives, expanding gases, spark discharge, and transient magnetic fields. The use of high-energy techniques for wire drawing, rolling, extrusion, and forging is mentioned.

Watts, A. F., and Harleman, Dorsie C., "Why Form Explosively?" The Tool Engineer, 44 (4), 109-112 (April, 1960). F-1-0-51

A general discussion of the work performed at Lockheed Aircraft under an Air Force Contract is presented.

Wesley, R. H., "Dynaforming", Final Report MRT 65-110 (56SH-0083), Convair, General Dynamics Corporation, Fort Worth (January, 1960). F-1-0-52

This report covers the research effort expended during 1959 on the Dynaform project at Convair. Comprehensive metallurgical tests were undertaken to determine

the effects of high-energy-rate forming on certain materials as well as the effect of the shock wave alone. Studies indicate that a sufficient amount of energy absorbed by a workpiece would conceivably change inherent physical properties such as specific-damping capacity.

Williams, C. P., "Evaluating Explosive Metal Forming", Journal of Metals, 12 (1), 33-36 (January, 1960). F-1-0-53

A number of tests which were conducted by Du Pont during their investigation of the potentials of explosive forming are presented. The most important aspect of their work was in the devising of a mathematical model to predict the behavior of various metals under static deformation on the basis of mechanical properties. The theory was compared with experimental cup-draw tests and the correlation on a statistical basis was found to be valid.

Zernow, L., and Lieberman, I., "Explosive Forming", Mechanical Engineering, 83 (12), 62-65 (December, 1961). F-1-0-54

The use of explosive charges for forming, sizing, compaction, forging, and perforation is covered. The work being conducted at Aerojet-General is discussed in general terms.

Zernow, Louis, "Physical Principles of Explosive Forming", Metals Review, 33 (1), 6 (January, 1960). F-1-0-55

The article reports a general lectùre on explosive forming given by Mr. Zernow at the ASM Utah Chapter meeting. It discusses the applications of explosive forming and areas of additional required development. Aerojet is using a liquid explosive named AEREX for their work.

"Explosive Forming at Aviation Institutes" (Translations from Russian articles on Explosive Forming, Explosive Punching of Holes in Railroad-Car Production, and Shock Wave Forms Metal), Science and Technology Section, Air Information Division, Washington, D. C.; AD 266482. F-1-0-56

The advantages of high-energy-rate forming over conventional metalworking techniques are discussed. Experiments at NIAT (Scientific Research Institute of Aircraft Technology), where explosive forming is utilized particularly for deep drawing, are cited. A schematic diagram of the experimental unit is presented. Regular high-energy-rate fabrication techniques were being used. The experiments proved that maximum deformability in deep-drawing operations remained practically unchanged at deformation rates up to 50 meters per second; hence the conclusion that the plastic properties of metals can be utilized at deformation rates beyond the present capabilities of conventional methods.

"Explosive Metal Forming and Electro-Hydraulic Effect; Survey of Soviet Literature", AID Report 60-108 (December 14, 1960); AD 250074. F-1-0-57

This bibliography contains 13 references to Russian articles dealing with high-energy-rate forming techniques for the fabrication of materials. Abstracts are given.

Articles by the following authors are referenced: Karyshev, Kononenko, Kuzmin, Markusha, Pikhtovnikov, and Yutkin.

"Explosive Forming", Aircraft Production, 22 (3), 82-85 (March, 1960). F-1-0-58

The article contains a discussion of the advantages of explosive forming in water-pit installation. The water-pit and the difficult materials processed successfully with this technique are described.

"Explosive Forming: A Consideration of Basic Principles and Phenomena", Aircraft Production, 22 (2), 62-65 (February, 1960). F-1-0-59

An analysis of the velocity of strain propagation, covering the longitudinal as well as transverse waves, critical impact-velocity studies, and studies of the causes of brittle-failure are reported.

"Explosive Forming Goes With a Bang", American Machinist, 113 (7), 120-121 (April 6, 1959). F-1-0-60

This article reports on the Western Metal Show giving brief summaries of papers of work at Aerojet, Ryan, and Convair.

"Explosive Forming – Successor to the Heavy Press?", American Machinist, 102 (27), 47-48 (December 29, 1958). F-1-0-61

This article covers the state-of-the-art in explosive forming as of the date of publication of the article.

"Blasting Metals Into Fancy Shapes", Business Week (1682), 94-96, 98 (November 25, 1961). F-1-0-62

A general description of the various techniques of high-energy-rate forming is presented. The article is primarily for review by businessmen and is not written in technical terms. Explosive, spark, magnetic, and gas forming are discussed as to advantages, costs, and present state-of-the-art for each.

"Lockheed Shocks Hard Alloys Into Shapes It Wants", Business Week, 84 (January 12, 1957). F-1-0-63

This experimental forming method, called shock forming, can shape hardened and tempered alloys that are all but impossible to fabricate. It can be used for drilling holes

in superstrength steels (done by using a converted stud driver actuated by a 22-caliber cartridge into a captive piston punch), for expanding tubing, and for draw forming. Shock forming is based primarily on the same principle which allows a piece of straw to pierce a telegraph pole during a tornado. If the forming tool travels faster than sound, it precedes the shock wave that causes work-hardening and consequent breakage.

"Explosive Forming", Electronics, 31 (42), 24-25 (October 17, 1958). F-1-0-64

Convair has found that dynamite and underwater arcs shape sheet metal without machinery.

"Explosive Forming Research Active", Light Metal Age, 17 (2), 16-17 (April, 1959). F-1-0-65

A critique is given of the presentations on high-energy-rate metal forming given at the 11th Western Metals Congress. Some of the work being accomplished at Ryan, Boeing, Aerojet General, and Lockheed is discussed.

"Explosive Forming", Light Metals, 34 (275), 115-116 (April, 1961). F-1-0-66

Some of the work on explosive forming in England by Rolls-Royce Ltd, D. Napier and Son Ltd, P. E. R. A., and the Ministry of Aviation is discussed. PETN Primacord type explosive has found the greatest number of applications.

Dies made of Kirksite or epoxy-plastic are not recommended for more than a few parts since they tend to distort and fail to hold tolerance. Ductile iron has been found to be most suitable for dies since it does not increase in size with the stresses normally encountered and it has the ability to withstand, without damage, the explosive shocks imposed.

A fundamental study of the physical metallurgy of the process is being made at Fort Halstead, and it is expected that the method will be employed as a standard process at one of the Royal Ordnance Factories.

"Some Possibilities of Explosive Forming", Machinery (London), 94 (2409), 63 (January 14, 1959). F-1-0-67

Conclusions were that explosive forming offers considerable promise as a means of overcoming some of the difficulties with which the production engineer is confronted, particularly in connection with certain of the newer difficult-to-work materials. The comparative simplicity of the plant required is likely to be one of the principal attractions of this process.

"Explosive Forming of Metals", Mechanical Engineering, 81 (12), 78-79 (December, 1959). F-1-0-68

The ability of a metal to be formed by explosives is discussed as a direct function of the following factors: a mechanical property, per cent elongation, maximum amount of plasticity available through explosive forces, temperature of the metal, medium used for force transmission, and type, amount, and shape of explosive charge.

"Explosive Forming Tames Tough Metals", Metalworking, 15, 32-36 (May, 1959). F-1-0-69

Tailored explosions are being harnessed to solve fabrication problems on high-strength alloys. One-shot explosive forming can produce parts difficult or impractical to make with standard methods.

"Production Explosive Forming on a Predictable Basis", Product Engineering, 30 (16), 26-27 (April 20, 1959). F-1-0-70

Attempts are made to rationalize an increase in elongation due to the difference between the static stress-strain curve and the dynamic curve. It is believed that the ultimate and yield strengths of materials under the dynamic conditions of explosive forming are considerably above those obtainable in static tests. Some of the work performed at Aerojet is discussed.

"Du Pont Reports on Explosive Forming", Steel, 145 (21), 74-76 (November 23, 1959). F-1-0-71

The article presents some interesting characteristics of explosive forming and shows evidence that the shock wave and not the pressure wave does the work. Various parts formed with explosives, from an 8-foot-diameter dome to venturies, are discussed. The following advantages are listed for the process: single shot forming, finish sizing, improved mating of parts, and hardening of austenitic steels.

"Explosive Forming Goes Commercial", Steel, 145 (24), 98-100 (December 14, 1959). F-1-0-72

This article describes in general the work being performed at Ryan Aeronautical with the explosive-forming process. Pictures are shown of some difficult parts they have formed.

"Explosive Forming Tackles Big Tube", Steel, 143 (23), 128 (December 8, 1958). F-1-0-73

An eleven-foot-long rocket booster is formed with explosives in a 7-ton die made by Chromalloy Corporation of Edwardsville, Indiana.

"Explosives Form Space Age Shapes", Steel, 143 (8), 82-86 (August 25, 1958). F-1-0-74

This article discusses what is being done with explosive forming, who is doing it, and uses for it. At Olin Mathieson's Explosive Division, metal fracturing and cutting with explosives is being investigated.

"Explosive Forming Blasts Complex Shapes in Fraction of Time by Conventional Methods", Western Metalworking, 17 (4), 52-53 (April, 1959). F-1-0-75

Experimental work in explosive forming at Ryan Aeronautical Company is described. A single blank has been formed into two different side-by-side shapes of different depths. PETN, a blanket-type explosive resembling linoleum, was used.

"Shock Forming With Explosives", Metalworking Production, 101 (11), 448-449 (March 15, 1957). F-1-0-76

The article is a study of the early development of high-energy-rate forming. One section describes experimental work at Convair using a low-explosive (expanding-gas) powered hammer which led to the development of the Dynapak. Most of the article deals with work at Lockheed. The work was concerned with: (1) punching holes, (2) pressure forming with low explosives, and (3) pressure forming with high explosives.

Armstrong, E. I., "Can Explosive Forming Solve Your Design Problems?", Iron Age, 186 (21), 85-87 (November 24, 1960). F-1-0-77

The article tells about the work being done at Rocketdyne Division of North American Aviation, Incorporated, in the field of explosive forming. In addition to forming operations, the author mentions other metalworking operations which have been performed with explosives at Rocketdyne. Explosive welding, extrusion, and blanking are discussed. The economics of explosive-forming operations are discussed.

Lambert, P. F., "Developments in Explosive Forming", Machinery (London), 95 (2437), 131-135 (July 29, 1959). F-1-0-78

The author presents explosive forming as a new development in metalworking and a possible solution to many forming problems. He divides explosive forming into two types – (1) pressure forming with propellant type explosives, and (2) shock-forming with explosives of high order – and then describes each of them. At the end, he gives some advantages and limitations of explosive forming, the current status of the process, and some of the future applications.

Dick, John H., "Explosives Promise New Era of Cheaper, Better Forming", Steel, 142 (1), 346 (January 6, 1958). F-1-0-79

A brief and general discussion of the explosive forming of metals.

Cox, F. A., and Mellinger, E. F., "Explosive Forming", Aircraft Engineering, 32 (377), 201 (July, 1960). F-1-0-80

This article discusses explosive-forming work at Ryan Aeronautical Company. Ryan has used four types of explosives - dynamite, prima-cord, PETN Sheet, and gunpowder.

"Explosive Forming of Metal Plates", Engineering, 189, 695 (May 20, 1960). F-1-0-81

This article is a review of other published work on explosive forming.

"Explosive Forces in Metalworking", Wire and Wire Products, 36 (9), 1153 (September, 1961). F-1-0-82

The article gives a brief description of the explosive forming process and lists a few other applications of explosives to metalworking.

"Explosive Forming of Metal Plates", Engineer, 209 (5449), 655 (April 15, 1960). F-1-0-83

This article gives a review of the work being done at the Crayford Works of Vickers-Armstrong (Engineers), Limited, in the field of explosive forming. The experiments conducted used 30 grains to 80 grams of Tetryl. It was shown that a hemispherically shaped explosive gives better results than a cylindrically shaped charge. The pressure plate was found to be essential to prevent wrinkling of the formed plate. The experiments were performed underwater and the die was under a vacuum of 29 inches of mercury.

"High Energy Forming to Gain Popularity", Steel, 148 (14), 82-85 (April 3, 1961). F-1-0-84

The article is from a meeting of the American Society of Tool and Manufacturing Engineers and is a general outline of developments in the high-energy-rate metalworking field. It is sub-headed by the three main energy sources, explosives, expanding gases, and electricity. Each of these is broken up into the various metalworking operations performed. Some operations discussed are forming, forging, swaging, powder compaction, and extrusion. There are also descriptions of various types of equipment and the companies which make them.

"How Explosives Form Space-Age Parts", Steel, 148 (23), 86-88 (June 5, 1961). F-1-0-85

The write-up presents the work being carried out at Aerojet-General Corporation in the field of explosive forming. It gives experimental results, materials which have been formed, types of dies used, and contours which have been formed.

"High Speed Forming of Metal Plates", Metallurgia, 62 (372), 144-145 (October, 1960). F-1-0-86

This article is based upon an experimental investigation of explosive forming conducted at the Crayford Works of Vickers-Armstrong (Engineers), Limited. A one-twelfth scale model of the dome end of a pressure vessel was the piece formed. The experimental equipment is described and the results of the experiment are given. It was found that explosive forming is most advantageous where small quantities of a special shape are needed or in forming metals which cannot be formed by conventional means.

"Progress in Western Metalworking", Western Metals, 15 (3), 78 (1957). F-1-0-87

This article discusses early work at Lockheed Aircraft where explosives were used to punch holes and expand tubing.

"Jet Engine Parts Now Formed by Explosives", Materials in Design Engineering, 50 (4), 197-198 (October, 1959). F-1-0-88

This article tells about the production of jet engine parts at Ryan Aeronautical Company. The article describes the shapes being formed, the materials and explosives being used, and the facilities in use. Some advantages it lists for the process are: (1) elimination of work hardening and springback, (2) use of inexpensive dies, and (3) replacement of massive, expensive machines.

"Ryan Uses Explosives on Hard-to-Form Metals", Product Engineering, 30 (16), 27 (April 20, 1959). F-1-0-89

The article describes Ryan Aeronautical Company's explosive-forming operations.

"Rocket Chamber Domes Explosively Formed", Electrical Engineering, 79 (1), 78 (September, 1960). F-1-0-90

Aerojet-General Corporation's in-production method of explosive forming Polaris end enclosures is described. They are able to form these 0.040-inch-thick domes within a tolerance of ±0.002 inch.

"Exploding the Myths of Explosive Forming", American Machinist/ Metalworking Manufacturing, 105 (13), 79 (June 26, 1961). F-1-0-91

This article gives information on explosive forming uncovered in studies conducted at Aerojet General Corporation. One thing mentioned was that, contrary to popular belief, springback and residual stresses do occur in explosively-formed parts but to a lesser extent than in conventionally formed pieces. Also, recent applications of explosive metalworking are discussed including fabrication of refractory metals, compacting of powders, welding, and forging.

Gibbs, Katye M., "Explosive Forming: A Report Bibliography", Prepared by Armed Services Technical Information Agency (February, 1962); AD 270900. F-1-0-92

This bibliography was prepared by ASTIA in response to numerous inquiries concerning the use and application of explosive energy in metalworking processes. Reports available from ASTIA are identified as ASTIA documents and were selected from both the ATI and AD collections covering the periods from 1942 through 1952 and from 1953 to the present. Within each of these categories, military reports are arranged alphabetically by source and title; reports prepared by Department of Defense contractors are listed alphabetically by source, contract, and then by title. Citations to open literature, commercial papers, and patents also appear alphabetically by author or title within separate categories.

Orr, James P., "Explosive Forming", Automation, 8 (10), 159-160 (October, 1961). F-1-0-93

A general article in explosive metalworking.

Rinehart, John S., "Explosions Form Missile Parts", Missiles and Rockets, 5 (48), 72-74 (November 28, 1959). F-1-0-94

The author tells how high explosives and propellants differ in the manner in which they generate energy. Then he shows that the placement of the charge is important and depends on the type of metalworking operation to be performed. The explosive operation distributes the loading force more evenly than does a conventional press.

Orr, James P., "Explosive Forming Has Many Advantages: One Big Disadvantage", Society of Automotive Engineers Journal, 69 (6), 57-59 (June, 1961). F-1-0-95

Some of the advantages of explosive forming listed by the author are: (1) amount of available forming force, (2) forming speed, (3) cost reduction, (4) reduced springback, and (5) work hardening. The one disadvantage he discusses is the amount of time required for loading and unloading the die. There is also a discussion of explosive forming at elevated temperatures. One of the die designs used and tooling for explosive forming are also discussed.

Stuckenbruck, L. C., "Explosives Cut Costs", Iron Age, 186 (17), 59 (October 27, 1960). F-1-0-96

At Rocketdyne Division of North American Aviation, Incorporated, they have used explosive forming to square the ends of over 2000 tubes at a savings of about $10,000.

Stambler, Irwin, "Explosive Forming Breaks Fabrication Bottleneck", Space/Aeronautics, 30 (5), 50-52, 54-55 (November, 1958). F-1-0-97

This article tells about some of the work done at Aerojet-General, one of the pioneers in the explosive-forming field. It gives the type of setup they used and also lists the metals they formed. Their results are said to have indicated no adverse effects on the microstructure or hardness of the metals.

Savitt, Jacob, "Explosives Form Tubes With and Without Dies", American Machinist, 103 (12), 135-137 (June 15, 1959). F-1-0-98

The author describes the free forming of tubes with Primacord explosive. The OD varied only 0.01 inch along the length. The forming of other shapes with dies is discussed. Cutting and punching operations are also mentioned.

Thrower, G. C., and Lieberman, D., "Stampings for the Space Age – By Explosive Forming", The Tool and Manufacturing Engineer, 46 (6), 123-126 (May, 1961). F-1-0-99

The paper covers in detail the preparation of the material blank, shaping of the charge, location and types of facilities, detonation of explosives, and various metal-working operations which can be performed (such as truing, forming, forging, and powder compaction).

Kemeny, G. A., "Method of Securing Using an Explosive Charge", U. S. Patent No. 2,978,796 (April 11, 1961). F-1-0-100

The invention described attaches blades to a rotor. The end of the blade contains an explosive charge. This end is inserted in a space on the rotor which is just large enough for the blade. Then the charge is detonated and the blade end assumes the shape of the space in the rotor thereby securing the blade in place.

Littlehale, P. E., "Means for Splicing Cable", U. S. Patent No. 2,213,224 (September 3, 1940). F-1-0-101

The invention described is an explosively operated cable splicing tool.

Maiwurm, P. S., "Apparatus for Securing a Tube or Tubes in a Body Member", U. S. Patent No. 2,779,279 (January 29, 1957). F-1-0-102

This device consists of an explosive charge within a tube to be secured. The charge is detonated and forces the tube against the body member. The tube assumes the shape of the cavity in the body member and becomes securely fastened.

Modrey, J. H., "Explosive Terminal and Method of Firing", U. S. Patent No. 2,909,758 (October 20, 1959). F-1-0-103

The main part of the apparatus described is a hollow electrical terminal. The hollow part is filled with explosive so that, when detonated, it forces the terminal wall against the material to which it is joined and secures it there. The charge can also be used to join a wire to the terminal. The heat generated by the explosion can be used to melt solder for further connections.

Muller, J., "Power-Operated Press Device", U. S. Patent No. 2,633,094 (March 31, 1953). F-1-0-104

The machine described can be used for forging, extruding, or drawing metals. It utilizes an explosive which, when detonated, sends out a pressure wave to force a piston against the material to be worked.

Teeple, G. H., Jr., "Apparatus and Method for Forming Self-Aligning Bearings", U. S. Patent No. 2,947,063 (August 2, 1960). F-1-0-105

This invention is for the swaging operation of putting ball bearings in the bearing housing. A punch is powered by an explosive charge and impacts against the housing side. This presses the housing over the ball. The housing then rebounds just enough to permit the ball to turn freely.

Temple, R., Jr., "Method of Forming Bonds", U. S. Patent No. 2,038,913 (April 28, 1936). F-1-0-106

An explosive charge is used to drive an element into one of the pieces to be joined which is in turn pressed against the other piece and leaves an indentation so that they cannot be separated.

Temple, R., Jr., "Explosively Actuated Press", U. S. Patent No. 2,149,641 (March 7, 1939). F-1-0-107

This press operates by the detonation of an explosive adjacent to a piston. The pressure of the explosion forces the piston head against the workpiece thus compressing it.

Temple, R., Jr., "Method for Fastening Sheet Material to Supports", U. S. Patent No. 2,666,252 (January 19, 1954). F-1-0-108

The invention described consists of an explosive charge which, when detonated, drives a stud through sheet metal and into a support thereby fastening the sheet securely.

Huston, F. P., Burrows, L. A., and Lawson, W. E., "Boiler Construction and Method of Producing Same", U. S. Patent No. 2,412,886 (December 17, 1946). F-1-0-109

Bolts are used to hold together the fire sheet and the wrapper sheet of a boiler. There is a little space between the male and female threads where the boiler can leak.

The purpose of the invention is to seal this space by means of explosives. The end of the bolt is hollowed out and filled with explosive. This charge is then detonated causing the bolt to expand, sealing it to the sheets.

Davis, C. O., "Method of Joining Objects", U. S. Patent No. 2,367,206 (January 16, 1945). F-1-0-110

By the use of this invention, two pieces of tubing can be explosively joined. The two pieces are butted against one another and a sleeve is placed over them. This sleeve is wrapped in two places (one over each of the tubes) with a single strand of Primacord. The explosive is detonated crimping the sleeve into each tube and joining them together.

Mead, G. A., "Method of Making Joints", U. S. Patent No. 9,286,382 (December 3, 1918). F-1-0-111

The purpose of this invention is to bond two adjacent ends of rails together so that there is continuous electrical contact. Terminals are installed in holes in the rails. The terminal is hollow. A blank cartridge is placed in each and is detonated by a firing pin attachment which is clamped onto the rail and terminal. The explosion causes the terminal to expand and form a tight joint with the rail.

Jones, I. N., "Method of Forming Sheet-Metal Bodies", U. S. Patent No. 939,702 (November 9, 1909). F-1-0-112

The invention consists of a mold made in sections. A sheet of metal is placed in or on the mold. A high explosive is detonated in the proximity of the sheet metal forcing it against the mold. Then the mold is dismembered to remove the finished workpiece. The part can also be formed in a series of explosive operations. This is one of the earliest U. S. patents on explosive forming.

Gentzsch, Gerhard, "Bearbeitet und Zurammengestellt", Nr. 19/610925 GE/GK, Verein Deutscher Ingenieure, VDI-Dokumentationsstelle, Literaturzusammenstellung (1961). In German. F-1-0-113

A bibliography on high-energy-rate forming. It contains 170 references to reports written in English, German, or Russian. It has a chronological listing of references, a periodical index, an author index, and a subject index. The references are arranged by subject.

Johnson, Walter C., "A Method of Generating Fluid Pressure for Tube Joining or Embossing, Stamping, of Metal Sheets and Such Like Operations", British Patent No. 21840 (September 23, 1897). F-1-0-114

This patent describes a method of joining tubes. The apparatus utilizes an explosive which, when detonated, generates a pressure wave forcing a plunger against an enclosed liquid. This liquid transfers the energy through a network of pipes to the tubes. The inner tube expands against the outer one and forms a tight joint.

"Explosive Forming", AID Report No. 60-87, Science and Technology Section, Air Information Division, Washington, D. C. (November 14, 1960), Translated from Izvestiya Vysshikh Uihebnykh Zavideniv (Gas-Punch Stamping of Sheet Material), Mashinostroyeniye (7), 87-95 (1960); AD 248404. F-1-0-115

Staff members of the Khar'kov Aviation Institute, under the supervision of Professor Pikhtovnikov, have continued the investigation of a high-energy cold-forming technique previously developed by Pikhtovnikov at the Institute's Department of Aircraft Construction. In this work they (1) determined the hydrostatic pressure required for deformation of sheet material, and (2) developed a method for calculating pressure transmitted to the workpiece by the explosive charge. The experiments and calculations were made for explosive forming in open dies with round or elliptic orifices. However, the equation for the explosive charge can also be applied for explosive forming in closed-impression dies, if a correction coefficient for each type of explosive being used is employed. In the case of a round die orifice, a shell with constant curvature is obtained. The equation is derived for calculating gas pressure produced by the explosion of an ammonite ball of a known radius placed at a known distance from the sheet being formed.

"Progress Report No. 2 by the Panel on Forgings and Extrusions of the Materials Advisory Board Committee on the Development of Manufacturing Processes for Aircraft Materials (AMC)", Report No. MAB 139-M(F2) Materials Advisory Board, National Research Council, Washington, D. C., Contract DA 36-039-SC-76436 (June 8, 1959); AD 219034. F-1-0-116

A number of projects dealing with forgings and extrusions are reviewed in this report. Programs dealing with explosive forging and explosive extrusion are among those reviewed.

Close, Gilbert C., "Facts About Explosive Metal Forming", Modern Machine Shop, 108-113 (May, 1959). F-1-0-117

The author tells about the work done at Aerojet-General Corporation in explosive forming. He describes the experimental work done and the instruments used to measure properties under dynamic conditions. Some important advantages of the process are listed. The article stresses the importance of safety precautions during explosive forming operations. Production techniques developed are described.

Cole, D. W., "Dynaforming, Phase I - Preliminary Explorations", Interim Report No. 1-8, MRT 56-110, December 12, 1957 to March 25, 1959, Convair, General Dynamics Corporation, Fort Worth. F-1-0-118

This report is a summary of the research effort at Convair in the high-energy-rate forming field. Tests conducted with aluminum and stainless steel alloys employed explosives with velocities ranging from 5000 FPS to 21,000 FPS. The following operations were investigated: tube piercing, blanking, forming over a male die, forming over a female die, forming in a cavity die, embossing or coining, stretching, and plate-bending.

Cross References.

C-2-1 Gives a general discussion of explosive forming.

C-2-2 Presents photographs of explosive forming.

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| C-2-5 | Discusses explosive metal-forming techniques in detail. |
| F-0-0-3 | Briefly discusses explosive forming. |
| F-2-0-1 | Discusses high-energy-rate forming in general. |
| F-2-7-1 | Reviews explosive forming in general terms. |
| F-3-0-4 | Presents a section drawing of an experimental explosive press. |
| G-1-1-1 | Covers explosive forming in general. |
| H-0-2 | Covers fundamentals of explosive forming and identifies operations which are presently feasible. |
| H-0-5 | Discusses explosive forging. |
| H-7-1 | Describes development work in Canada on explosive forming. |
| J-1-3 | Discusses explosive hardening of metals. |
| J-3-13 | Describes an invention for working metal and punching holes with explosives. |
| K-0-26 | Studies mechanism of fracture caused by detonation of explosives. |
| K-1-77 | Discusses the formability and ductility of a material subjected to an explosive load. |

Chemical System

Aluminum. F-1-1

Adams, D. S., Harrison, V. S., and Orr, J. P., "High Energy Forming of Metallic Sheet Materials", Report No. 61B072 of the Ryan Aeronautical Company for U. S. Army on Contract DA-04-495-ORD-1921; WAL TR 624.5/1; AD 265035. F-1-1-1

Tests were conducted on various materials to study the feasibility of forming them with explosives. The metallurgical characteristics of these materials which resulted from being explosively formed were determined. Results of the work indicated that this manufacturing technique lends itself to the forming of parts having intricate shapes, and is particularly practical for the fabrication of parts large beyond normal machine capacity. Metallurgical tests show that there was no detrimental effect on materials as a result of this forming process. Indications are that some materials must be formed at elevated temperatures.

The mechanical properties of the materials tested were improved by the extreme pressures applied by explosive forming.

Materials tested were 5086 and 7075 aluminum alloys, 301, 302, and 355 stainless steel alloys, 6Al-4V titanium alloy, and 4340 steel.

Alder, J. F., and Phillips, V. A., "The Effect of Strain Rate and Temperature on the Resistance of Aluminum, Copper and Steel to Compression", Journal of the Institute of Metals, 83, 80-86 (1954-1955). F-1-1-2

Stress-strain curves were determined during compression to 50 per cent reduction of height at constant true-strain rates in the range of 1 to 40 inches per inch per second. The stress for a given strain increased with strain rate in a fair agreement with a power law. The power index tended to increase with temperature and at higher temperatures also increased with the strain.

Bradlee, Charles R., "High Forming Rates for High Production", ASTME Report No. SP 60-105, presented at the Creative Manufacturing Seminars (1960-1961). F-1-1-3

The various high-energy-rate forming techniques are compared with mechanical-conventional-press methods in terms of productivity, size of parts, complexity of parts, and capital investment.

In making the comparison the extrusion of aluminum cans is considered. It is shown that the strain rates in a high-production mechanical press can often exceed those obtainable with slow-burning propellent systems.

DeGroat, George H., "Explosive Forming – The Planemaker's Newest, Hottest Tool", American Machinist, 103 (12), 131-143 (June 15, 1959). F-1-1-4

Some of the early work conducted at North American Aviation, Columbus, Ohio, is discussed. The forming of aluminum tank shells from rolled and welded sheet-metal cones is described. The effects of different types of explosive charges are discussed. The relationship between standoff distance and pressure is covered.

Hasemeyer, Earl A., "Forming at High Energy Rates: Explosive Forming", Report No. DFR-IN-33-59, Army Ballistic Missile Agency, Redstone Arsenal, Alabama (June 30, 1959). F-1-1-5

A study to determine the feasibility of flaring a hole and drawing a shallow part by a high-energy-rate forming method was conducted with aluminum alloy 5058-H34. Though flaring of the hole was successful, forming of the shallow draw was only partially successful. A 5-inch elliptical hole was successfully flared in two stages by explosive forming. Diamond-pyramid-hardness values were increased from 93 DPH to 105 DPH. These changes in hardness values indicated that the final work hardening was equivalent to the 3/4 hard or H36 condition. There was a 22 per cent reduction in thickness on the flared hole and about a 10 per cent reduction in thickness on the formed part.

Ida, Noble N., "Explosive-Forming Techniques at Martin-Denver", ASTME Report No. SP 62-84, presented at Creative Manufacturing Seminars (1961-1962). F-1-1-6

This report describes an investigation at the Martin-Denver plant of the feasibility of forming one-piece structural shells of unlimited dimensions. No conventional capability existed for forming these parts. Scaling laws were developed. The effects of explosive forming on the mechanical and structural properties of 2014 aluminum alloy were determined, and limits of formability were established. Some work was also conducted on sandwich forming and on the explosive forming of integrally machined blanks. A paraffin coating was used to prevent oxide build-up on the surface of the workpiece prior to forming and to act as a forming lubricant. Forming of aluminum cups with welds was also investigated.

Schiffel, J. W., "Concussion Forming, Ultra-Strength Steels, and Metal-Tape Tube", Quarterly Progress Report Part 1, Ingersoll Kalamazoo Division, Borg-Warner Corp., Michigan, July-September 1958, Contract NOrd-15719 (November 7, 1958); AD 206539, AD 216723, AD 210784. F-1-1-7

An investigation was made of the effects of thickness, material, material hardness, surface condition, explosive quantity, and standoff distance on the explosive forming of aluminum alloys (2024-O, 2024-T, and 6061-T) and steel alloys (AISI 4130, MBMC No. 1, Vasco 1000, and AISI 1020). Three 10-inch-across flat-octagon specimens were formed under each set of conditions. After the specimens were placed in the die set and the stack filled with water, the charge was placed at the specified standoff distance on the centerline of the die and fired. The specimen was formed down into the die by the concussion. Plots and discussions are presented on the bulge depth as a function of the charge weight, material hardness and thickness, and the standoff distance.

Stuckenbruck, L. C., and Martinez, C. H., "Explosive Forming in the Missile Industry", Machinery, 67 (3), 99-106 (November, 1960). F-1-1-8

Some of the experimental explosive forming work conducted at Rocketdyne is discussed. They have successfully formed such metals as aluminum, copper, nickel, tantalum, zirconium, columbium, 15-7Mo and 17-7 stainless steels, René 41, and 6Al-4V titanium. An explosive forming facility is located at the Rocketdyne Propulsion Field Laboratory in the Santa Susana Mountains near Los Angeles. Production runs have been made on some small tubing details and on tank sections where the quantity of parts produced exceeds 100 pieces.

Ward, R. J., Jr., "New Ways to Form Metal", Product Engineering, 32 (39), 106-107 (October 16, 1961). F-1-1-9

The Methods Research and Development Branch of the Marshall Space Flight Center's Fabrication and Assembly Engineering Division are investigating three advanced metalforming methods - electric discharge, magnetomotive and chemical-explosive techniques. Presently, Ryan Aeronautical and Propellex Chemical Division of Chromalloy are handling the R&D for the government agency.

The government is interested in the forming of missile bulkheads of 200-inch diameter; larger than can be formed on conventional machines.

Some discussion of electric discharge and magnetic forming is also given in general terms.

"Process Development Program for the Explosive Forming of T54El Missile Skins", Final Summary Report, Technical Document 42060, Serial Number 24905, Honeywell Ordnance Division to Picatinny Arsenal on Contract DA-11-022-501-ORD-2662 (June 21, 1960). F-1-1-10

This report covers the research and development work performed by Honeywell in the development of the explosive forming of contoured aluminum skins for missile nose-cone applications. An analysis of costs of forming the skins by high-energy-rate methods as compared to the more conventional forming methods indicates that the explosive method is the most economical. Information is also included on the use of various charge types to obtain the desired formed part. Die materials used in this program were cast steel. Line charges of primer cord were found to be more successful than point charges with the initiation at top or bottom equally successful. The mechanical properties of the parts after forming were found to be significantly improved. The best condition found for forming was the W condition with aging after forming to derive the desired properties. Welding with 435 wire as a filler metal was not desirable as weld cracking occurred during the forming operation. 5356 filler wire produced ductile welds which were satisfactory after the welds were planished.

"Warhead Skin Fabrication Techniques", Technical Document 21759 Serial Number 21843, Honeywell Ordnance Division to Picatinny Arsenal on Contract DA-11-022-501-ORD-2662 (August 1, 1959). F-1-1-11

This report presents a survey of the warhead skin fabrication techniques used throughout industry as well as techniques investigated or developed by Minneapolis-Honeywell.

The processes investigated cover hydraulic bulging, flow turning, spinning, explosive forming, impact extrusion, and expanding-mandrel bulging. Included is a brief description of the various processes and their characteristics, and an analysis of the best application of these processes to a selected group of warheads.

"Martin Company Research Men Come Up With 'Explosive' Idea", American Metal Market, 69 (94), 23 (May 16, 1962). F-1-1-12

It is reported that Dr. A. A. Ezra, Chief of the Technical Development Section of Martin's structures and aerophysics department, and F. A. Penning have developed a set of workable scaling laws to work with explosive forming. Len Berman (Chief of the Materials Engineering Section) and Noble Ida are using these scaling laws to establish the formability limits of metals – particularly aluminum alloys of different thicknesses and sizes. It is reported that Mr. Ida has patented a process for forming a perfect hemisphere from a piece of aluminum only slightly thicker than a piece of paper.

Even though several separate explosive shots were used, the thin metal did not split and the finished product had a uniform thickness. The process involves the use of a lead plug which is placed over the stock to be formed. The plug distributes the shock wave of the explosive charge more evenly and controls the mass movement of the metal causing the metal to stretch evenly. An air cushion system and free forming processes are also being investigated.

"Explosive Forming Procedure Nears Production Stage at Martin", Missiles and Rockets, 9 (6), 24-25 (August 7, 1961). F-1-1-13

Explosive forming techniques being developed at Martin Company, Baltimore, are expected to reach production status within a year. Scale model torus tanks are currently being formed explosively, considerably reducing the weldage and piece work involved in conventional fabrication. Reduction from 40 separate pieces to 12 pieces and reduction of welding footage by 40 per cent was obtained through explosive forming.

Some of the work on the large elliptical-dome sections being performed at Ryan Aeronautical Company is discussed. The sections are 15 feet in length and 8 feet wide and are made from 5086 aluminum alloy.

"High-Energy-Rate Metalworking Today", The Tool and Manufacturing Engineer, 48 (1), 61-68 (January, 1962). F-1-1-14

A general discussion of the various high-energy-rate techniques and energy sources is given. The following correlation formula is given:

$$(H/a)^2 = 0.4W/StR^2$$

where H = depth of forming of the center of the blank, a = radius of unsupported portion of the work blank, W = charge weight in grams, S = yield stress of the material, t = blank thickness, and R = standoff distance.

A formability rating has been assigned to each of various materials with 1100 aluminum the most formable and 301 stainless steel (full hard) the most difficult. Work being conducted at the following companies is discussed: Rocketdyne, U. S. Naval Ordnance Test Station, China Lake, Michelson Lab., Ryan Aeronautical Co., Boeing Airplane Co., and Bendix Corporation. Explosive forming, welding, electrohydraulic forming, and pneumatic-mechanical forming are discussed.

"Explosive Forms Aluminum Door", Iron Age, 186 (12), 100-101, September 22, 1960. F-1-1-15

This article gives a good outline of the method used in forming this specific part. The main factors to be considered are type, size, and shape of the explosive; distance between the bottom of the charge and the top of the forging stock; die material and design; and the container shape. Work conducted at American Potash and Chemical Corporation served as the basis for this discussion of forging doors from 7075 aluminum alloy. Strength and elongation data for the forged piece are given.

"Explosive Size Missile Warhead", Steel, 147 (6), 99 (August 8, 1960). F-1-1-16

This article presents the work being done at Parish Pressed Steel, Division of Dana Corporation on forming large missile warheads from 6061-T6 aluminum alloy. They use Primacord for the explosive and water for a transmission medium. Their die is split and has vacuum seals.

"High Explosives Shape Airplane Fuel Tanks", Automotive Industries, 19 (10), 41 (November 15, 1958). F-1-1-17

This article tells about the explosive forming of fuel tanks at Columbus Division of North American Aviation, Incorporated. The tanks are explosively formed in a water pit using an evacuated die.

"NASA Studies High-Energy Forming", American Machinist/Metalworking Manufacturing, 105 (20), 85 (October 2, 1961). F-1-1-18

NASA studied electric-discharge and magnetic forming as possible methods for producing large bulkheads of aluminum for the Saturn and Nova space vehicles. They came to the conclusion that both methods were incapable of handling the large blanks needed and so decided to use explosive forming methods. The work is being handled by several private industrial firms including Ryan Aeronautical Company and the Propellex Division of Chromalloy Corporation.

"Explosive Forming Big Radar Reflector", Modern Metals, 16 (7), 52 (August, 1961). F-1-1-19

The article concerns the forming of radar reflectors by Ryan Aeronautical Company. These aluminum pieces are 78 inches in diameter and 22 inches deep. New developments in dies are discussed.

Orr, J. P., "Explosive Forming Domes", Paper presented at the American Rocket Society Solid Propellant Rocket Conference, Baylor University, Waco, Texas, January 24-26, 1962, Ryan Aerospace Company, San Diego, California (January 15, 1962). F-1-1-20

A general description is given of the techniques which could be utilized to form large dome sections for rocket tanks. The forming of a dome from flat sheet, the forming of a dome from a welded preform, and the preforming of gore segments to be assembled and welded to make a large dome were considered. The main consideration in forming the large dome sections by explosive forming techniques is the maintenance of a consistent or controlled thinning of the material as the domes are being formed. Information on the construction of dies and the formability of various aluminum alloys is given.

Truelock, D. W., "A Summary of Explosive Forming Projects From August, 1959, to May, 1962", Report No. 2-22300/2R-13, Chance Vought Corporation, Dallas, Texas (June 6, 1962). F-1-1-21

This report presents a summary of research work performed in explosive forming by Chance Vought Corporation. The initial phase was directed toward the determination of forming parameters and the solution of problems associated with maintaining adequate control over the explosive forces. The second phase involved investigation of explosive forming as a production process. Data are presented on charge size, standoff distance, charge shape, and part configuration. An evaluation of an explosively formed thin-wall 8-inch-diameter tube with a nonconcentric shape is presented. The forming of large-diameter Saturn dome ends is discussed.

Ida, N., and Snyder, J. T., "Determination of Formability Limits for 2014 Aluminum Alloy When Explosively Formed", Report No. IR-62-6, Martin Company, Denver, Colorado (February, 1962). F-1-1-22

Investigations which were conducted on the following subjects are discussed:

(1) Thickness and deflection analysis of selected parts formed by explosives
(2) Paraffin coating of materials to improve ductility during forming
(3) Explosive-sizing studies
(4) Testing of a nonreinforced epoxy-faced concrete die
(5) Forming of shells using the plug-cushion principle
(6) Sandwich forming
(7) Forming of shells by straight bulging with no thinout
(8) Fabrication of 24-inch hemispherical shells from the 2219 alloy
(9) Investigation of the explosive forming criteria for different configurations of welds
(10) Determination of the mechanics of welding by explosives
(11) Design, construction, and calibration of a master die assembly
(12) Forming of integral skirt to dome assembly.

Hall, A. W., and Lieberman, I., "Explosion Forming Closures for Large Solid Propellant Rocket Cases", Final Report, Aerojet-General Corporation, Downey, California, for USAF on Contract No. AF 04(611)-8395 (1962). F-1-1-23

The object of this program is to establish explosive forming parameters and develop the techniques required to produce 120-inch diameter closures suitable for use in large solid propellant motor cases. Primary emphasis is being placed on the use of free-forming dies with closure configuration being maintained by the shape and orientation of the explosive charge. The potential of utilizing the ice die approach for sizing the free-formed part or forming from a flat blank will be explored where free-forming results indicate the need.

Burns, J. J., Robinson, C. W., and Sams, J. H., "An Investigation of Formability Limits and Explosive Charge Parameters for Explosively Formed 2014-O Aluminum Domes", Report No. IR-62-25, Martin Company, Denver, Colorado (July, 1962). F-1-1-24

The formability limits for explosive forming flat 2014-O aluminum alloy blanks into thin shells of evolution have been investigated using free-forming techniques. Curves defining formability limits (w/D vs D/t) are plotted from experimental data. The curves developed are for circular blanks with diameters 40 per cent larger than the diameter of the formed shape.

It was found that the contour of the free-formed shape is only weakly dependent on charge shape or standoff distance. A spherically-shaped charge was found to be more efficient than a cylindrical charge, and a standoff distance of D/3 was preferred to a standoff distance of 2D/3, not for better formability but for more efficient use of explosives.

Magdich, E. M., "Explosive Forming of Bulkheads, Gores, and Solar Concentrator Leaves", Report No. 62B004, Ryan Aeronautical Co., San Diego, California, for NASA on Contract No. NAS-8-851 (January 10, 1962). F-1-1-25

This report deals with three separate tasks: development of a technique for explosive forming 70-inch-diameter bulkheads, stretch-forming of and optical tests on aluminum concentrator leaves, and fabrication of 320-inch bulkhead gores. The forming of very large bulkhead segments was conducted in steps with intermediate anneals between the forming operations.

The types of tooling used are shown. The forming of the 320-inch bulkhead gores was not completely successful due to the massiveness of dies required for the gore segments.

<u>Cross References</u>.

E-2-18 Studies free forming of a thin aluminum plate by a small charge of high explosive.

F-1-2-2 Gives method of explosive forming a cone or hemisphere from aluminum.

F-1-6-3 Describes the explosive forming of missile tank ends from wide aluminum sheet.

F-1-6-4 Describes developmental work on the explosive forming of aluminum using tetryl as the explosive.

F-1-6-5 Discusses explosive forming of aluminum alloys.

F-1-7-5 Describes a study of the explosive forming of sharp-angle cones from aluminum alloy work pieces.

F-1-7-6 Describes work on high-energy-rate forming of aluminum.

K-1-57 Studies fracture in aluminum from explosive forming.

K-2-24 Discusses results of some explosive forming studies.

Chemical System

Copper. F-1-2

Anderson, G. D., Doran, D. G., Hempy, F. S., and Kells, M. C., "Cratering by High Velocity Microparticles", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). F-1-2-1

The cratering characteristics of various metals and non-metals are described with special emphasis on cratering in copper. Impacting particles of different materials moving at different velocities were studied.

"Explosive Forming From Blank to Cone in One Easy Step", Steel, 145 (23), 152 (December 7, 1959). F-1-2-2

A method of explosively forming cones or hemispheres is presented. A slight modification of a deep-drawing process permits a kind of metal gathering which produces a cone with walls thicker than the original blank. Materials investigated were copper, aluminum, and stainless steel.

Kiyota, Kankichi, "Experiments of the Plastic Deformation of Thin Metal Plates Under Blast Type Loading", Reprint from Memoirs of the Faculty of Engineering, IX (2), Kumamoto University, Kumamoto, Japan (1962). F-1-2-3

This report concerns an investigation of the type of plastic deformation which occurs in a diaphragm gage subjected to explosive loading in air. It had been previously found that the diaphragms deform into a semi-spherical shape underwater. The author investigated the deformations which occurred in air because sometimes they were conical. He describes the apparatus used to make measurements of impact load and velocity change. Finally, he uses mathematical relationships determined experimentally to show that although the pressure is evenly distributed across the metal plate, the plate will not necessarily deform into a semi-sphere.

Cross References.

B-4-7 Discusses the impacting of copper with a copper projectile.

F-1-1-2 Studies effect of strain rate and temperature on the resistance of copper to compression.

F-1-1-8 Discusses experimental work on explosive forming of copper.

Chemical System

Magnesium. F-1-3

Chemical System

Nickel. F-1-4

Herb, Charles O., "Ryan's Split-Second Explosive Forming", Machinery, 65 (11), 102-107 (July, 1959). F-1-4-1

This article describes some of the work conducted at Ryan in explosive forming under water. Gages of materials formed range from 0.016 to 0.063. Materials formed were Inconel, René 41, Hastelloy, 321 and 17-7 stainless steel, and titanium alloys. The use of explosives for blanking as well as forming has been demonstrated. They feel that work hardening of the material is less pronounced when parts are formed with high explosives than when it is formed by conventional methods.

"Blast It", American Machining, 98 (22), 173 (October 25, 1954). F-1-4-2

This article tells of explosive forming a Monel metal fan hub in the shape of a truncated sphere. The metal was welded into a cylinder, placed in a die with the required spherical contour, and partly filled with water. Dynamite was placed inside at water level and exploded. The welds were undamaged, and the shape was formed without cracking. There was no waste of metal and no trimming or annealing was required. Wall thickness was uniform. Cost was 15 per cent less than spinning.

Wolf, Paul J., "Superalloys Formed With Explosives", The Tool Engineer, 41 (6), 78-82 (December, 1958). F-1-4-3

The author describes the mechanisms of explosive forming, the materials which have been formed, and the types of explosives used. The operations of forming, swaging, forging, extruding, and cutting and flattening by explosive techniques are described.

Cross References.

F-1-1-8 Discusses experimental work in explosive forming nickel.

F-1-8-6 Reports on the explosive forming of nickel alloys on a production basis.

Chemical System

Refractory Metals. F-1-5

McGovern, Donald R., "A Study of Explosive Forming Selected Refractory Metals", Final Report, Propellex Chemical Division of Chromalloy Corporation for USN, Bureau of Weapons on Contract No. NOw 61-0832-c (April 1, 1962). F-1-5-1

The work performed includes an investigation of the explosive forming of selected refractory metals to optimize the strain-rate conditions. Also reported is work on the development of the most suitable transmission media for achieving maximum formability. The effects of temperature on explosive forming of refractory metals were investigated to a maximum of 1000 F. The three basic materials investigated were arc-cast molybdenum (0.2 per cent titanium), tungsten, and columbium alloy (Cb-74).

"Explosive Forming of Refractory Metals", ARTC/R&D Final Technical Report No. 2011, Chromalloy Corporation for USN, Bureau of Weapons on Contract NOas 59-6265-c (December, 1960). F-1-5-2

Explosive forming molybdenum and molybdenum 1/2 per cent titanium alloy resulted in greater elongation than was previously obtainable with these materials using conventional forming methods. The maximum percentage elongation was achieved after forming at a strain rate of 0.7 to 0.9 x $10^7$ microinch per inch per second. It was also found that the percentage elongation achieved in tungsten, and therefore the formability, increases with increasing strain rate. This suggests that even greater percentages elongation could be obtained with higher detonation velocity explosives than are now available. Sintered molybdenum was found to have a peak workability point in mid-range strain rates while arc-cast material seems to increase in workability as the strain rate is increased. The alloys tested were found to be very susceptible to "notch effect".

Perkins, R. A., "Report of the Committee on Refractory Metals", Report MAB-154-M(1), Volume 11, National Academy of Sciences, National Research Council, Washington, D. C., for Office of the Director of Defense Research and Engineering on Contract No. DA-36-039-sc-76436 (October 15, 1959). F-1-5-3

Areas for additional research in the explosive forming of refractory metals are recommended and the state-of-the-art is described.

Philipchuk, V., "Metal Fabrication by Explosives", American Society of Mechanical Engineers, Paper 60-MD-4, p 5 (1960). F-1-5-4

National Northern Division of American Potash and Chemical Corporation has been testing the explosive fabrication of Zircaloy-2, molybdenum, titanium alloys, and other materials. The operations of interest are sizing, forming, forging, joining (welding), and compacting powders. Extrusion, shearing, and some other operations were of minor interest. The pressure-time work curve shows the differences in stress-strain applications between conventional and explosive forming. Explosive pressure is transferred through damping media with sufficient energy to cause metal to behave plastically.

"Explosives Shape Market in Metal Forming", Chemical Week, 85 (6), 75 (August 8, 1957). F-1-5-5

Chromalloy Corporation received a "substantial" contract from the Navy Bureau of Aeronautics for research on the explosive forming of refractory metals. They are tailoring their own charges from glycerine trinitrate, trinitrolene, trimethylene trinitramine, triethylene glycol dinitrate, tetramethylene tetranitramine, pentaerythritol tetranitrate, and lead styphnate. Metals to be studied are Mo, Cb, W, Ta, and their alloys. Higher densities of Mo and W powders can be attained by explosive forming than by slip casting.

Cross References.

F-1-0-91 Gives information on explosive forming of refractory metals at Aerojet.

F-1-1-8 Discusses experimental work on explosive forming refractory metals

F-1-6-1 Deals with experimental explosive forging of refractory metals.

## Chemical System

### Low Alloy Steels. F-1-6

Albrecht, R. L., "New Horizons in Forging Techniques", Metal Forming and Fabricating, 20 (7), 15-16 (July, 1958). F-1-6-1

A part of this article deals with Air Force-sponsored work by National Northern in explosive forging. An outline of the results expected is presented.

Hartbower, Carl E., "Mechanics of the Explosion Bulge Test", Welding Journal, 32, Supplement 33-s-341-s (July, 1953). F-1-6-2

The need for a semiworks-scale test of weldments featuring simple geometry and controlled loading led to the adoption of bulge-test methods. The extension of hydraulic-bulge-testing techniques to full thickness of ship plate was accomplished by the detonation of an explosive suspended in air over the test plate. The explosive was used as a means of obtaining the high forces required to develop bulges in thick plate. The depth of bulge produced by various combinations of weight and standoff of explosive are indicated by empirical relationships. Where a set-strain level was desired, more than one loading would be used until the desired strain level was obtained. This method of testing weldments provided a biaxial strain which was not possible with the previously used hydraulic test due to the thickness of the plate being tested.

Lieberman, I., "Explosive Forming Program Utilizing Wide Sheet Steel", Aerojet-General Corporation Final Technical Engineering Report 61-7-787a, for USAF, ASD on Contract No. AF 33(601)-38921 (October, 1961). F-1-6-3

This report covers work performed at Aerojet-General Corporation on the explosive forming of missile tank ends from wide sheet. A total of sixty-eight steel sheets in a range of thicknesses, widths, and lengths were used in the compilation of the data. A die for 54-inch-diameter rocket-motor heads was used in this investigation and gages of material from 0.040 to 0.350 inch were used. The materials utilized were Vascojet 1000, aluminum alloys, and AMS 6434 steel. Application of the process to the forming of 77-inch-diameter steel domes is illustrated.

Some information on explosive welding at National Northern is also contained in this report.

May, D., and Patterson, R. A., "An Investigation of the Relative Deformation of Various Metals by Concussion Forming Methods", Project Report No. SPDIR 20, Ingersoll Kalamazoo Division, Borg-Warner Corporation, Contract No. NOrd 15719, Problem 1 (July 6, 1959); AD 203762. F-1-6-4

The report describes the results of an explosive forming study where tetryl was used as the explosive charge. Test specimens were 4-inch diameter cups drawn from a 10-inch octagon blank. The following materials were tested: AISI 4130, 1020, MBMC #1, Vascojet 1000, 2024 aluminum, and 6061 aluminum. Various gages and hardnesses of materials were tested. It was found that the bulge volume formed bore a fixed ratio of about 8.2:1 to the bulge depth. There was nothing in the results to imply any physical or structural changes that would not have occurred during cold forming these materials.

The following characteristics of tetryl are listed: energy release, 988 calories per gram; blasting power (TNT ref), 1.26; detonation rate, 25,000 feet per second.

Tardif, H. P., "Shape - Fasten - Engrave - Test - Materials With Explosives", Materials in Design Engineering, 49 (2), 82-87 (February, 1959). F-1-6-5

The explosive forming of 4130 steel, Types 302 and 347 stainless steel, aluminum alloys, and titanium are discussed. The types of systems used and the advantages of each are presented. The punching of holes through metals and the fastening of metals using explosive rivets or driven studs are examined. Two methods of explosive engraving are given; the first uses the shaped charge effect and the other uses a consumable stencil.

Bulge tests and triaxial loading tests are suggested areas for research using explosive charges.

"Explosive-Forming and Associated Programs", Aerojet-General Corporation Report No. 2606-01QE-2 (June 30, 1960). F-1-6-6

The feasibility of forming 0.040-inch-thick domes from flat steel stock has been demonstrated. Domes of high-strength steel having thickness variations within ±0.002 inch have been formed.

The forming of domes of moderate depths from flat banks of cold-rolled and solution-treated B-120VCA titanium appears to be feasible. The feasibility of explosive sizing subscale samples to within 0.010 inch of desired contour has been demonstrated. Data indicate that the sandwich sheet tends to correct the buckling problem while the hold-down pressure and peripheral restraint on the blank tend to correct the wrinkling.

"Symposium-Wide, Close-Tolerance Steel Sheets", Final Technical Engineering Report TR 61-7-787a, Douglas Aircraft Company, Inc., for USAF on Contract AF 33(600)-42793 (October, 1961). F-1-6-7

Two papers were presented which deal with high-energy-rate forming. The first is by I. Lieberman and L. Zernow of Aerojet-General Corporation on "Explosive Forming Program Utilizing Wide Sheet Steel" and the second is by J. C. Venuto of National Northern Division, American Potash and Chemical Corporation on "Evaluation and Explosive Welding of Steel Sheets".

In both papers the fabrication difficulties encountered in the preparation of details from large thin steel sheets is explored. Some information on the past accomplishments of both companies is given.

"Explosive Metal Forming of Rocket Cases", Aircraft and Missiles Manufacturing, 1 (11), 69 (November, 1958). F-1-6-8

This article describes work on rocket cases 11 feet long by the Propellex Chemical Corporation, Edwardsville, Illinois, a Division of Chromalloy Corporation.

"A 14-Foot Dome of H-11 Tool Steel Set Largest Ever by Explosive Forming", Metalworking News, 11 (October 2, 1961). F-1-6-9

A planned 14-foot-diameter dome made of 1/2 inch thick H-11 tool steel at Ryan Aeronautical Company is reported. Work at Boeing Airplane Company with exploding-gas mixtures is discussed. One of the limitations reported is that gas pressures over 15 atmospheres cannot be used. This method cannot be used on metals requiring heating before forming.

Andrepont, Wilbur C., Turner, Stewart W., and Thompson, James C., "Facilities Availability and Requirements for Fabrication of Case Segments and Closures for Large Solid Propellant Rocket Motors", ASD-TR-61-44, Air Force Systems Command, Solid Systems Branch, Los Angeles, California (September, 1960); AD 273794. F-1-6-10

This report describes a study to determine current industry capability for fabricating case segments and closures for large segmented solid-propellant rocket motors. Only current state-of-the-art materials and manufacturing processes were considered. The fabrication of end closures by spinning, explosive forming, and welding is discussed.

Cross References.

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| B-4-1 | Study of transient behavior in a thick circular steel plate deforming under explosive attack. |
| B-4-3 | Discusses computer programming to simulate the effect of a cylindrical charge detonated in intimate contact with a steel plate. |
| B-4-4 | Describes optical technique for measuring surface oscillations of steel plates while they deform under explosive attack. |
| F-1-1-1 | Describes experiments on low-alloy steels to study the effect of explosive forming on their formability and metallurgical characteristics. |
| F-1-1-2 | Studies effect of strain rate and temperature on the resistance of steel to compression. |
| F-1-1-7 | Investigates the effect of concussion forming on steel alloy properties. |
| F-1-7-6 | Describes work on high-energy-rate forming of steels. |
| F-1-7-7 | Describes shock forming of steel alloys with gunpowder. |
| F-1-8-3 | Discusses processes for high-energy-rate extrusion of steel alloys by explosives. |
| K-2-4 | Deals with explosive forming of cast iron. |
| K-2-24 | Discusses results of some explosive forming studies. |
| K-3-2 | Discusses four types of failures in steels concerned with embrittlement. |

## Chemical System

### Stainless Steels. F-1-7

Cadwell, Gil C., "Spark Forming Goes to Work", American Machinist/ Metalworking Manufacturing, 105 (23), 126-129 (November 13, 1961). F-1-7-1

Some of the work being conducted at Rohr Aircraft, Chula Vista, California, with electric-spark devices is presented. Rohr has one machine with 6 kv and 4300 joules output and another with 14.4 kv and 11,500 joule output. The machines have been used mainly for the bulging of tubing with the spark-discharge method. Some work has also been conducted with exploding-bridge-wire systems. Aluminum and 321 stainless steel materials are mentioned as having been formed.

Claus, J., Meredith, D., and Sutch, F., "Manufacturing Methods for Hot Structures", Final Report (June 1, 1959-September 15, 1960), Boeing Airplane Company, Seattle, Contract AF 33(600)-39542; AD 250054. F-1-7-2

An evaluation of both hydraulic and explosive forming techniques for the bulging of ultra-thin-wall super-alloy tubing is reported. An explosive forming die was designed to expand various diameter, preswaged tubes to 1.125 inch diameter. One end of the die incorporated a 15° transition angle while the opposite end had a conventional 10° transition angle. 321 stainless steel tubing was used for the test. Primacord charges were suspended along the centerlines of the tubes by inserting them in common drinking straws. The charge was detonated from both ends. The results indicated that the location of the charge along the centerline axis of the tube was critical. A series of small charges produced better results than a single charge in 0.750-inch-diameter tubing and above this diameter it was less critical. The best forming medium was water. A maximum elongation of 30 per cent was obtained.

Strohecker, Daniel E., "Explosive Forming of PH15-7Mo Stainless Steel", Report No. NA59H-634, North American Aviation, Columbus (September 11, 1959). F-1-7-3

This study was initiated to determine the effects of pressure and impulse on the formability of PH15-7Mo stainless steel in a free-draw-cup test. The variation of formability possible between mill-run material and ground stock was included. The use of composite shock-wave propagation media appeared to be a feasible method of using higher velocity explosive charges on materials which perform best with a lower velocity explosive.

Strohecker, Daniel E., "Deep Drawing Without Presses", Report No. NA61H-76, North American Aviation, Columbus (May 4, 1961). F-1-7-4

The use of explosive forming in the production of missile dome ends was successful. The dome ends were 12 inches in diameter and were made from 350 stainless steel in the annealed condition. The gage of the material was 0.040. It was found that the most important factor in deep-draw forming with explosives was the holddown pressure

applied to the draw ring. A number of different charge weights, standoff distances, and charge configurations were used with success. The use of plastic laminates in a cast kirksite die body proved to be efficient for only 10 dome ends. Production quantities requiring a larger number of parts should be made on solid dies. The metallurgical evaluation of the material after explosive forming indicated that superior properties could be obtained through modification of subsequent heat-treatment cycle.

Tardif, H. P., "The Explosive Forming of Conical Shapes by Metal Gathering", CARDE Technical Memorandum 280/59, Canadian Armament Research and Development Establishment (October, 1959); AD 231999. F-1-7-5

Preliminary tests carried out at C. A. R. D. E. to study the forming of sharp-angle cones by an explosive metal gathering process are discussed. In this process the metal accumulates or gathers together giving an increase in wall thickness as compared with deep-drawing. One disadvantage of the process is that under explosive pressure the friction between the blank and the die is too high, preventing the blank from flowing inside the die. In a modified arrangement the blank is placed inside the cavity, and positioned either by its own bevelled edge or by a machined groove around the die. Upon detonation of the explosive, the blank is probably accelerated at high velocity towards the bottom of the die folding and thickening continuously from its edge to take the shape of the conical cavity. An absorber material was used over the blank to prevent pitting since the work was conducted in air. The following materials were investigated: types 304, 316, and 321 stainless steel; 2024-T3, 1100-H14, and 6061-T6 aluminum; and copper.

Wickesser, Arthur, Jr., "Recent Developments in Explosive Forming", Design News, 15 (6), 195 (March 14, 1960). F-1-7-6

This article covers work performed at Grumman Aircraft on high-energy-rate forming. Uniaxial and biaxial strain rates were correlated with ductility and temperature for AISI 303 and 310 stainless. The results are shown in three dimensional plots. The discussion of attempts to form the following types of aircraft parts is given: rocket combuster of .050 thick 321 stainless steel in an epoxy resin die, transition element in an exhaust system from .025 thick 321 stainless steel in a steel die, gun seal of .065 thick 321 stainless steel die, beaded sheet .100 thick and .068 thick 304 stainless steel sheet formed on a kirksite die, and the doomed section on an open end die. .090 and .190 thick 7075-O aluminum, 4130 steel and 4-1-3 MoV titanium were formed. The following conclusions were reached:

1. High energy rate forming lends itself most readily to short-run forming operations.
2. Steel dies are required for accurate forming of most metal shapes.

"Explosive Forming Socks Tough Alloys in Shape to Thwart Thermal Thicket", Western Metals, 15 (5), 57-58 (May, 1957). F-1-7-7

A modern application of gunpowder is as an "explosive tool" for shock forming high tensile stainless, titanium, and steel alloys. Gunpowder and high explosives show

promise in punching, upsetting, expanding, swaging, forming, cupping, and bulging operations, and in working otherwise impossible materials.

The Lockheed research program, under Glen Rardin, is divided into three phases: (1) punching holes, (2) pressure forming with low explosives, and (3) pressure forming with high explosives.

Dethloff, R. C., "Development of High Performance Rocket Motor Case", Engineering Quarterly Progress Report No. 6, Budd Company, Philadelphia, Pennsylvania, for USA on Contract No. DA36-034-ORD-3296, Project No. OMS-5010-1190800-51-04 (October 1-December 31, 1960); AD 250275. F-1-7-8

Investigation is being made of explosive forming ellipsoidal heads of AM355 and of deep drawing ellipsoids of titanium alloys.

Cross References.

F-1-1-1 Reports on the formability and metallurgical characteristics of stainless steels with respect to explosive forming.

F-1-1-8 Discusses the experimental explosive forming of stainless steels.

F-1-1-14 Describes a correlation formula for assigning formability ratings to various materials with 301 stainless steel (full hard) the most difficult to form.

F-1-1-21 Discusses the explosive forming of stainless steel tubes.

F-1-2-2 Gives a method for explosive forming a cone or a hemisphere from stainless steel.

F-1-4-1 Describes explosive forming stainless steel under water.

F-1-6-5 Discusses explosive forming of stainless steels.

F-1-8-6 Reports on explosively forming stainless steels on a production basis.

K-2-24 Discusses results of some explosive-forming studies.

## Chemical System

### Titanium. F-1-8

Dickenson, Thomas A., "Explosives Form Titanium Too", American Machinist, 103 (12), 138 (June 15, 1959). F-1-8-1

A possible die design is shown which tends to concentrate the load on the workpiece. Additional assembly time is required for this type of die, however, a reduction in energy requirements is obtained. Stronger dies must be made for the semi-closed system for proper safety. The use of porous inserts at the bottom of the die where the vacuum may be pulled through is a novel approach to elimination of part marking due to the vent hole in the die. The work was conducted at Lockheed Aircraft Corporation. Titanium cup tests were conducted with the 6Al-4V alloy. Two-inch-diameter cups were drawn as test pieces from six-inch-diameter blanks.

Echols, T. H., and Hamm, B. R., "Development of Explosive Forming Titanium Alloy Helmet Shells", Letter Progress Reports, Ryan Aeronautical Company, San Diego, California, to USA, QM R&E Command, on Contract No. DA-19-129-QM-1540 (1960-1961). F-1-8-2

The progress report dated December 15, 1960, described the preliminary experimental work with various drawing lubricants. It was reported that a 50-50 mixture of Electro-film 22T and Superbrite 1160 glass beads provided an excellent lubricant on the heated dies used for forming the titanium helmet shell. The results obtained on additional tests have not been as successful. This mixture appears to "break down" at the temperature used (up to 1250 F) to heat the dies to form the material.

Howery, J. W., "Development of a Process for the Extruding of Titanium and Steel Alloys by Use of Explosives", Interim Engineering Report No. 1, Manwk 58-5-32, Extrusions, Inc., Caldwell, New Jersey, for USAF on Contract No. AF 33(600)-37428 (1958); AD 228068. F-1-8-3

The development of a process for extruding titanium and steel alloys by the use of explosives includes (1) a theoretical investigation and design of equipment, (2) initial extension tests, and (3) an extrusion test of a more complex shape. The development and procurement of an economical explosive or propellant potentially capable of producing pressures up to 200,000 psi for time intervals as long as 3 seconds is considered essential. Tentative time-pressure relationships were established for the explosive extrusion of soft metals, medium-carbon steels, alloy steels, and titanium. These were discussed with vendors of liquid and solid propellants or explosives, and several vendors expressed confidence in being able to develop and produce economical liquid-propellant charges with the desired properties. A test program of die hardening was arranged at Hercules Powder Company, Kenvil, New Jersey. Several cast dies of Rexalloy A and Rexalloy 33 were produced and tested. An extrusion press is being designed, and vendors were consulted for instruments to record the extreme pressures and phenomenal exit velocities involved in the extrusion of metal by the explosive process.

Wick, Charles H., "Titanium Formed at Ford by Heating, Rolling and Exploding", Machinery, 63 (11), 184-189 (July, 1957). F-1-8-4

The article describes work being performed in the manufacture of jet engine compressor blades. The tooling which is used is described. The operation is essentially one of expanding a hollow blade in a closed die with the gas generated from a shotgun shell.

"Explosive Forming", Aircraft Production, 23 (4), 122-123 (April, 1961). F-1-8-5

Some of the findings of Ryan Aeronautical Company on the use of explosive forming are discussed. Ductile iron castings have been found to provide sufficient strength and absence of growth during the explosive forming operation. Alluvial sand instead of water as a shock transmitting medium has been useful in elevated temperature operations up to 1000 F. Titanium alloys have been successfully formed by the use of electrically-heated dies.

"Explosive Forming, Water-Pit Installation for the Working of Difficult Materials", Aircraft Production, 22 (3), 82-85 (March, 1960). F-1-8-6

It is reported that the Ryan Aeronautical Company is explosively forming titanium, 321 and 17-7 stainless steels, Inconel, and René 41 on a production basis. An eight-foot reinforced-concrete pit is used for the operation. Explosives used at Ryan include dynamite, tetryl, PETN, and cyclonite. Material thicknesses have ranged from about 0.016 to 0.063 inch. To indicate the increased elongation that can be expected where high-energy forces are employed, it is pointed out that 347 stainless steel, which is generally considered to be less than 50 per cent ductile prior to conventional forming, manifests 75 per cent ductility when it is explosively fabricated. Blanking of 6Al-4V titanium sheet 0.063 inch in thickness was reported by using a 160-gram charge of dynamite suspended 12 inches above the work.

"Explosive Forming of M-1 Helmets", Final Report No. 61B073, Ryan Aeronautical Company, San Diego, California, for USA on Contract No. DA-19-129-QM-1540 (July 24, 1961). F-1-8-7

This report covers the work conducted at Ryan Aeronautical in the forming of titanium helmets for the Quartermaster Corp. The helmets were formed at elevated temperatures in a step-type operation. Although they were successful in forming the helmets by this technique the multiple steps required would make this operation uneconomical. The type of tooling used on this program, the use of sand as a firing medium, and the techniques utilized in heating the part end dies were covered in this report. Due to the heating of the dies, insulated-explosive charges had to be used.

Cross References.

F-1-1-1 Reports on the formability and metallurgical characteristics of titanium alloys with respect to explosive forming.

F-1-1-8 Discusses experimental explosive forming of titanium alloys.

F-1-4-1 Describes explosive forming of titanium alloys under water.

F-1-5-4 Describes explosive forming of titanium alloys.

F-1-6-6 Demonstrates feasibility of explosive forming domes from titanium alloys.

F-1-7-7 Describes shock forming of titanium alloys with gunpowder.

J-1-4 Reports on the use of heated dies in explosive forming hemispherical shapes of titanium.

K-1-76 Discusses elevated-temperature explosive forming of titanium.

Chemical System

Other. F-1-9

Zupon, W. E., "Plasticity of Zircaloy-2 Under Explosive Loading", Zirconium Highlights, AEC Report WAPD-ZH-19 (July, 1959). F-1-9-1

This article summarizes the results of an experiment designed to determine the relative plasticity of Zircaloy-2 under explosive-loading conditions. Zircaloy-2 was formable. No adverse effects on the corrosion resistance of the material was observed.

## Forming

Electrical F-2-0

Gipe, C. W., "New Manufacturing Techniques - High-Energy Forming", Paper presented at the National Aeronautic Production Forum, Los Angeles (October 10-11, 1960). F-2-0-1

A general discussion of the various high-energy-rate processes as related to forming operations is given.

The electric-discharge method is said to produce 1,000,000 psi for a 2-3 microsecond duration at a cost of approximately 0.004 cents per shot. Methods of control are listed such as the power source, the size of the bridge wire between electrodes, and the type of material in the bridge wire.

Parr, J. Frederick, "Hydrospark Forming Shapes Space-Age Metals", Tool Engineer, 44 (3), 81-82 (March, 1960). F-2-0-2

The discharge of an electric spark under water produces a shock wave with energy sufficient to form metal parts. This article describes a production application of this method for forming tube parts at Republic Aviation.

"Explosive Forming", Electronic Industries, 20 (1), 100 (May, 1961). F-2-0-3

General Electric's electrospark forming methods are described.

"Electrospark Shapes Tough Metals", Steel, 148 (8), 33 (February 20, 1961). F-2-0-4

The article is about General Electric's work in electrospark forming.

"Explosive Forming With Electricity", Mechanical Engineering, 81 (11), 77-78 (November, 1959). F-2-0-5

Republic Aviation Corporation's work in forming with a rapid release of electrical energy is discussed. The experiments so far have produced a force of 5000 horsepower released in 40 millionths of a second. This energy can be used to form many metals which are very difficult to form by conventional means.

Brower, E. F., "Metal Forming With Hall's Magnetic Field", GA 3529, General Atomics Division, General Dynamics Corporation (October 12, 1962). F-2-0-6

This report discusses some of the unique characteristics of the magnetic-pulse metal-forming processes. It gives some examples of its application to date and points out in a general way some of the aspects of the design of magnetic-pulse-forming equipment.

Cross References.

A-2-0-9 General review of work on capacitor-discharge electrospark forming.

A-2-1-12 Discusses the general use of electric sparks for forming metals.

F-0-0-3 Discusses electrospark forming and mentions work being done in Russia.

F-1-0-15 Surveys methods of high-energy-rate forming.

F-1-0-17 Discusses applications of hydrospark forming.

F-1-0-21 Provides a brief background and a descriptive explanation of the use of electric spark and electromagnetic techniques.

F-1-0-22 Reviews various types of high-energy-rate forming which are being put into production.

F-1-0-32 Surveys recent work in the high-energy-rate forming field.

F-1-0-50 Discusses forming by spark-discharge and transient magnetic field techniques.

F-1-0-57 Bibliography of Russian literature concerning electrohydraulic forming.

F-1-0-62 Presents a business review of spark and magnetic forming.

F-1-0-64 Describes use of underwater arcs in forming sheet metal.

F-1-0-84 Gives a general outline of the development of electrical discharge metalworking.

## Electrical

### Aluminum. F-2-1

Caggiano, A., Christiana, J., D'Aguano, P., Hoppe, F., Inman, N., and Pfanner, G., "Capacitor Discharge Metal Forming", Interim Tech. Engr. Rpt. No. 5, Republic Aviation Corporation for USAF on Contract AF 33(600)-42920 (April, 1962). F-2-1-1

The energy-transfer phenomena in electro-hydraulic-metal forming is described. The variable parameters of energy level, inductance, initiation-wire material, diameter and length, gap distance, standoff distance, and liquid medium are evaluated relative to current, pressure, and deformation work. Optimum values for each of these parameters are established.

Techniques of calibrating the deformation work obtained in tubes expanded by the electro-hydraulic-forming process are described. Some mechanical properties of expanded aluminum tubes are presented.

"Sheet Metal, High Energy Forming Development", Final Report No. E9661-044, McDonnell Aircraft, St. Louis, Missouri (January 29, 1962). F-2-1-2

This report covers the work which was conducted at the McDonnell Aircraft Corporation to determine the feasibility of high-energy-rate forming by the controlled use of the electric-discharge method. Discharge voltages of 12 kilovolts maximum and capacitors with 630 microfarads maximum were used in this study. Voltages, capacitance electrode height, and gap were varied to obtain a forming pressure which would form a particular part to its desired shape.

Easier to form alloys, such as 321 stainless steel in the annealed condition, 5052-0 aluminum and 6061-0 aluminum were used in the forming test. Later, high-strength alloys such as L-605 and René 41 were tested. Various dies which had previously been used on explosive forming operations were used as test dies in this operation.

Cross References.

F-1-1-3 Compares electrical high-energy-rate forming technique with conventional mechanical press equipment. Extrusion of aluminum cans is used as an example.

F-1-1-9 Investigates electric discharge and magnetomotive forming techniques.

F-1-1-18 Gives NASA's conclusions that electric-discharge forming process is inadequate for forming aluminum bulkheads.

F-1-7-1 Covers electric-spark forming of aluminum.

Electrical

Copper. F-2-2

Cross References.

A-2-1-7 Covers experimental equipment for capacitor discharge electrospark forming of copper.

Electrical

Magnesium. F-2-3

Electrical

Nickel. F-2-4

Germann, R., and Shaver, C. J., "Formability of Inconel X", Final Engineering Report No. MNP 58-71, Republic Aviation Corporation to USAF on Contract No. AF 33(600)-38042; AMC-TR No. 59-7-767, Part III (November 30, 1959). F-2-4-1

A discussion of spark-discharge forming of Inconel X tubing is given. The tubes were 1-1/2 inches in diameter by 2 inches long. The workspace-discharge gap was centrally located in the tubes between two axial electrodes. The surrounding medium was distilled water which permits a high work output due to its low resistivity. Each tube was subjected to three discharges at 20,000 volts to produce the deformation. All tubes were free formed without fracture.

Some explosive-forming tests on a part with a re-entrant angle were conducted without success. Failure was caused by uneven distribution of the explosive force. A water bag rather than a water pit was used in the test setup.

"Forming Sheet Metal With Explosives", Machinery (London), 95 (2457), 1287-1290 (December 16, 1959). F-2-4-2

This article discusses explosive forming being done at Ryan Aeronautical Company. Information is given about types of explosives to use, facilities necessary, shapes of parts which can be formed, and materials to be used in die construction. Inconel, René 41, Hastelloy 321, 17-7 stainless steels, and titanium alloys can be formed easily by explosives. Operational details are given.

Cross References.

F-2-1-2 Provides data on the electrohydraulic forming of nickel-base alloys.

Electrical

Refractory Metals. F-2-5

"Electrospark Forming: New Way to Shape Hard-to-Form Metals", Iron Age, 187 (8), 98-99 (February 23, 1961). F-2-5-1

The article covers General Electric's work in electrospark forming. It mentions that General Electric has shaped titanium, columbium, beryllium-copper, and stainless steels. Some key advantages of the process are elimination of storage and handling problems associated with chemical explosives and elimination of the need for locating facilities in remote areas.

Cross References.

A-2-1-7 Covers experimental equipment for capacitor-discharge electrospark forming of refractory metals.

F-2-8-1 Describes experimental work on electric-discharge forming of refractory metals.

F-3-5-2 Discusses combining electrohydraulic forming with high-velocity mechanical forging in working with refractory metals.

Electrical

Low Alloy Steels. F-2-6

Cross References.

F-2-8-1 Describes experimental work on electric-discharge forming of steel.

Electrical

Stainless Steels. F-2-7

Feddersen, E. W., "Production Application of High-Energy Rate", Design News, 15, 104-109 (August 15, 1960). F-2-7-1

A general review of some of the work in high-energy-rate forming which has been conducted at Convair is given. Explosive forming, electric-spark forming, and pneumatic-mechanical devices are mentioned. A description of a ball joint made from two stainless steel tubes is presented.

"Spark Forming Works on Stainless", American Machinist/Metalworking Manufacturing, 105 (5), 80 (March 6, 1961). F-2-7-2

This article describes work being done in electrospark forming by General Electric, Chrysler, Convair, and Republic Aviation. General Electric has a capacitor bank rated at 27,000 joules and has been forming pieces up to 10 inches in diameter and 3/32 inch thick. Chrysler has been experimenting with forming Redstone missile parts by electrospark means. Convair is coming out with a commercial unit, Hi-Vo-Pac, capable of 15,000 joules. Republic, the first company to report the process, has contracted to study the effect of electrical-discharge forming phenomena on stainless steel.

Cross References.

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|---|---|
| A-2-1-7 | Covers experimental equipment for capacitor discharge electrospark forming of stainless steels. |
| F-1-7-1 | Covers electric-spark forming of stainless steel. |
| F-2-1-2 | Provides data on the electrohydraulic forming of stainless steel. |
| F-2-4-2 | Discusses explosive forming of stainless steels at Ryan. |
| F-2-5-1 | Covers G. E.'s work in electrospark forming of stainless steels. |

Electrical

Titanium. F-2-8

"Electrical Explosive Forming Technique Pushed", American Metal Market, 14 (February 17, 1961). F-2-8-1

Experimental work being conducted at General Electric on electric-discharge forming is discussed. Pieces up to ten inches in diameter and 3/32 inch thick have been formed. The following materials have been formed by this technique: titanium,

niobium, tungsten, molybdenum and certain steels and beryllium alloys. All experimental work was conducted at room temperature.

Republic Aviation was awarded a 22,900-dollar NASA contract to study the efficiency of high-energy-rate methods in shaping stainless steel and aluminum alloys.

Cross References.

A-2-1-7 Covers experimental equipment for capacitor discharge electrospark forming of titanium.

F-2-4-2 Discusses explosive forming of titanium alloys at Ryan Aeronautical Co.

F-2-5-1 Covers G. E.'s work in electrospark forming of titanium.

Electrical

Other. F-2-9

## Forming

Mechanical F-3-0

Goudreau, A. G., "Zero-Draft Forgings", Production, 48 (4), 68-71 (October, 1961). F-3-0-1

The experiences of the Bendix Corporation in obtaining and placing a Dynapak machine into production are presented in this article. It was found that dense grain refinement and 14:1 extrusions are possible with this equipment. Where extraction of the completed workpiece from the male die created problems, the female die was threaded so that the part would stay in the female die and could be unscrewed from it after extraction of the punch. The production use of this equipment is leading to many more uses than were originally contemplated. New forging techniques are also being developed.

Jackson, J. H., and Goodwin, H. B., "Forging and the Space Age", Metal Progress, 76 (1), 65-71 (July, 1959). F-3-0-2

A description of the use of a pneumatic-mechanical device for forging is given. A discussion of the operation of the system and its application to close-tolerance draftless forging is presented.

Kaser, R. A., "High Energy Impact Forming Program, State of the Art Survey", Interim Report TR 7-848 (I), General Dynamics Corporation to USAF on Contract No. AF 33(600)-43035 (June 8-August 8, 1961). F-3-0-3

The state-of-the-art of rubber-pad forming of sheet materials at velocities greater than those produced by the usual drop hammer or hydraulic press was investigated. Previous work in this field is reviewed. Some work is being done at increased pressures on the workpiece with existing equipment but no work is being done at velocities greater than fifty feet per second because of the limitations of existing rubber-pad forming equipment.

Previous work is described with particular emphasis on the type of equipment and instrumentation used. Conclusions drawn from the earlier work in the field are presented.

Peters, R. W., "Impact and High Velocity Forming, the Trend Toward Explosive Techniques", Tool Engineer, 39 (1), 83 (July, 1957). F-3-0-4

This article presents a section drawing of an experimental explosive press showing the firing mechanism and the manner of guiding the trapped rubber head. The author describes early advances toward new forming techniques and equipment, and gives initial proof of its capabilities.

Rippel, J. M., "High Energy Rate Extrusion Phase II", Westinghouse Electric Corporation, Blairsville, Pennsylvania, for USAF on Contract AF 33(600)-41948 (January, 1962). F-3-0-5

This investigation of the high-energy-rate extrusion process has been continued. Inertial separation, the tensile failure of the extrusion due to its rapid deceleration, imposes a serious limitation to a successful process for making 10-feet lengths in one piece. This report covers the investigation into the parameters that directly affect this phenomenon. These parameters include machine mass, investigated on both a 1210 model and an 1810 model Dynapak, billet size, and reduction ratio. Work on magnetic and mechanical deceleration is discussed with pictures and descriptions of extrusions made to date.

Monsees, Ralph G., "Steel Parts Formed on High-Energy-Rate Machine", Metals Progress, 80 (2), 74-75 (August, 1961). F-3-0-6

The article describes work which is being accomplished on a production basis with a Dynapak machine. The high pressure applied at great speeds permits parts to be extruded or forged in one stroke to close tolerances and with smooth surfaces without the surface contamination of conventional forging or extrusion processes. Most of the previous work on this type of equipment has been on the hard-to-work materials. Evidence is presented which indicates that the equipment has considerable potential for use on more common materials such as resulfurized steels.

Ottestad, J. B., "Dynapak (A High Energy Rate Machine Tool)", Reprint of a discussion on Dynapak presented at the 40th Metals Congress in Cleveland (1959). F-3-0-7

A description of the development sequence of a pneumatic-mechanical device trade named Dynapak by the Convair Corporation is presented. The machine developed was to have a forming-head velocity controllable between 1 and 5000 inches per second The range of energy produced was to be between 40,000 and 3,000,000 foot pounds. The machine had to be operable in open factory and laboratory areas. Repeatability of operations and low initial equipment cost were prime objectives. A discussion as to how these problems were solved and the final operational characteristics of the machine are presented.

Ottestad, J. B., "Applications of High Energy Rate Forming", ASTME Report No. SP 60-174, Presented at the Creative Manufacturing Seminars (1960-1961). F-3-0-8

Several typical parts which have been produced on a Clearing-Hermes high-energy-rate forming machine are used to demonstrate the capabilities of the equipment and to show the types of applications this equipment is suited for. It is noted that the only basic differences in the operation of high-energy-rate forming equipment and conventional equipment is the inertia of the material under the dynamic load and the extremely short time the material undergoes deformation. Some of the problems which still require research effort involve die design, die material, lubricants, billet configuration, handling devices, and properties of finished parts.

Tatarinou, Victor, "The Forging Process From a Hydrodynamic Point of View", Steel Processing, 32 (7), 446-447 (July, 1946). F-3-0-9

The article describes the forging process as being controlled by the following factors:

1. Temperature of heating.
2. Character of forging process affecting the direction of displaced material.
3. Velocity of plunging the tool into the piece subjected to forging affecting an additional dynamical resistance.

Based on these assumptions equations were developed to determine the power necessary to overcome the resistance of the material to forging. The derived equations were obtained from the fundamental hydrodynamic equations.

Kline, James A., "Expanding the Capabilities of the Pneumatic-Mechanical Process", Preprint of ASTME paper presented at the Creative Manufacturing Seminars (1961-1962). F-3-0-10

A comprehensive review of high velocity impact metalworking is presented which includes the following:

a. Selection of proper tooling in relation to the material being forged.
b. Tool loading resulting from extrusion and upsetting operations.
c. Response of materials to high velocity forming as compared to results with conventional forming methods.
d. Empirical relationships useful in estimating metal forming energy requirements.

"High-Energy-Rate Forming of Close Tolerance Parts", Aircraft Production, 23 (3), 80-86 (March, 1961). F-3-0-11

The process described in this article is an application of the piston-cylinder principle, in which the required forming pressures are obtained by gas pressure. It is one of several high-energy-rate processes developed by Convair and, it is claimed, has given remarkable results in finishing close-tolerance parts directly to size. The operational characteristics of the machine are described and some examples of parts which have been forged are presented.

"High-Energy-Rate Forming of Close Tolerance Parts", Aircraft Production, 23 (3), 80-86 (March, 1961). F-3-0-12

A review is given of the development of various high-energy-rate forming devices at Convair. Pneumatic-mechanical equipment (Dynapak), an electrical-discharge unit (Hi-Vo-Pak), and an electromagnetic-energy unit (Magnepak) are discussed. An economic analysis of a forging made with conventional press equipment and the same part made by Dynapak shows a considerable cost saving for the latter operation. Savings up to 60 per cent on material, 50 per cent on tooling, and 75 per cent on operating costs have been realized in a few production runs on forgings.

Kaser, Robert A., and Stratton, Frank A., "High Energy Impact Forming Program - Prototype Design Parameters Study Program", Report 7-848 (II), General Dynamics Corporation, San Diego, California, for the USAF on Contract AF 33(600)-43035 (February, 1962). F-3-0-13

Test procedures to determine the basic parameters of the prototype high-energy-rate rubber-pad sheet-metal-forming machine to be constructed in this program are described. Results of tests of the effects of energy and velocity on sheet-metal formability and the design parameters of the prototype machine are given.

Riordan, Thomas S., "Advances in Pneumatic-Mechanical Forming", ASTME Report No. SP 62-93, Presented at the Creative Manufacturing Seminars (1961-1962). F-3-0-14

A case study of the forging of several parts on a Dynapak machine is explored. Such factors as die design, lubricants, elevated-temperature forming, and the requirement for intermediate anneals are discussed. Some discussion of the limited production rate of the Dynapak is given with the expected advantages of new types of pneumatic-mechanical equipment which are now being marketed.

"U. S. Industries High-Energy-Rate Forging Machines", Machinery, 101 (2592), 154-158 (July 18, 1962). F-3-0-15

A discussion of the new U. S. Industries Incorporated pneumatic-mechanical machine designated Type 2600B is given. The machine has a maximum energy rating of 145,000 foot-pounds. Maximum closing velocity is 62 feet per second. Some of the typical parts which have been formed on this piece of equipment are described.

Cross References.

A-3-1-4 Gives a case history of evaluation and production with a Model 1210 Dynapak machine.

F-0-0-3 Discusses briefly pneumatical-mechanical forming.

F-1-0-15 Surveys methods of high-energy-rate forming.

F-1-0-17 Discusses applications of pneumatic-mechanical forming.

F-1-0-21 Provides a brief background and descriptive explanation of pneumatic-mechanical forming.

F-1-0-22 Reviews the various high-energy-rate forming facilities which are being placed into production.

F-1-0-28 Gives a general discussion of pneumatic-mechanical forming using a Dynapak machine.

F-1-0-50 Discusses forming by means of expanding gases.

F-1-0-60 Reports in brief summaries work at three companies.

F-1-0-62 Presents a business review of gas forming.

F-1-0-84 Gives a general outline of pneumatic-mechanical metalworking.

F-2-0-1 Gives a general discussion of high-energy forming.

F-2-7-1 Reviews pneumatic-mechanical forming in general terms.

## Mechanical

### Aluminum. F-3-1

Peacock, J., "Forming Goes Ultrasonic", American Machinist/Metalworking Manufacturing, 105 (24), 83-85 (November 27, 1961). F-3-1-1

This is the first report on the use of ultrasonics as an energy source for high-energy-rate forming. The report describes dimpling tests on A110AT titanium sheet and 7075 T6 aluminum which were conducted for Republic Aviation by Cavitron Ultrasonics.

It was found that the static force increases about 30 times when the vibrating punch contacts work. Friction forces appear negligible and it appears that hot-forming results can be obtained at room temperature.

Cross References.

E-2-39 Describes the development of the piston and cylinder arrangement for high-velocity, high-impact forming of aluminum.

F-1-1-3 Compares mechanical high-energy-rate forming with conventional mechanical press processes. Extrusion of aluminum cans is used as an example.

F-3-6-1 Gives results of tensile impact tests and describes changes in the properties of aluminum.

K-1-2 Describes use of a can plastometer to determine the resistance to compressive deformation of aluminum.

K-1-3 Describes high-velocity impact of aluminum sheet with spherical particles.

K-1-15 Investigates the influence of impact velocity on the tensile properties of aluminum.

Mechanical

Copper. F-3-2

Cross References.

F-3-6-1 Gives results of tensile impact tests and describes changes in the properties of copper.

F-3-6-3 Discusses experimental work on forming of copper with a Dynapak done at American Brake Shoe.

F-3-7-1 Discusses forging and extrusion with a Dynapak.

Mechanical

Magnesium. F-3-3

Cross References.

F-3-6-1 Gives results of tensile impact tests and describes changes in the properties of magnesium.

K-1-15 Investigates the influence of impact velocity on the tensile properties of magnesium.

Mechanical

Nickel. F-3-4

Mechanical

Refractory Metals. F-3-5

Carpenter, S. R., "Convair Reports on High-Energy Forming", American Machinist, 103 (6), 126-127 (March 23, 1959). F-3-5-1

High-energy-rate forming (Convair's Dynapak) is now producing extrusions from such hard-to-move metals as tungsten, columbium, zirconium, steel-jacketed sintered nickel, and titanium. It is making extrusions and forgings to closer tolerances and with greater savings in materials than is possible by conventional methods.

DeGroat, G., "Two HERF Techniques Team Up", American Machinist/Metalworking Manufacturing, 105 (24), 100-101 (November 27, 1961). F-3-5-2

This article discusses the techniques used in making 50 nested sets of 3 concentric 180° bend "U" tubes for commercial nuclear power reactors by NTH Products. Zircaloy-4 outer tubes which could not be formed conventionally were produced by combining high velocity mechanical forging with electro-hydraulic forming. The operations are described.

Orrell, F. L., Rabenold, D. G., and Rippel, J. M., "Pneumatic-Mechanical Extrusion of Refractory Metals", ASTME Report No. SP 62-05a, presented at the Creative Manufacturing Seminars (1961-1962). F-3-5-3

This paper discusses the extrusion of refractory metals conducted by Westinghouse on a Model 1210 Dynapak machine. Successful tests were conducted on all of the refractory metals. The process was particularly successful for ingot breakdown. Difficulty with tool breakage, mainly the punches, caused considerable difficulty in the program. With the simplification of tooling and the use of extrusion entrance angles, the same as are used in conventional extrusion processes, the difficulties were considerably reduced.

Rabenold, D. G., "Comparison of High Energy Rate (Dynapak) and Conventional Extrusion of Refractory Metals", Westinghouse Electric Corp., Blairsville, Pennsylvania, for USAF on Contract No. AF 33(616)-7842; AD 268774. F-3-5-4

Seven Dynapak extrusions of a Mo-25W-0.1Zr alloy were made to determine a hot-working, a cold-working, and an intermediate temperature for arc-cast material. Two billets were then extruded at each temperature on both a Dynapak and conventional press and evaluated for surface, dimensions, chemistry, hardness, tensile properties, and recrystallization behavior. This evaluation concluded that the surface of the Dynapak extruded bars was better and that both the temperature required for hot working, and the recrystallization temperature of cold-worked material were lower on the Dynapak machine.

Bufferd, A. S., Zwilsky, K. M., and Grant, N. J., "Hard Particle Strengthening of Refractory Metals for High Temperature Use Through Internal Oxidation", Final Report, New England Materials Laboratory, Inc., Medford, Massachusetts, for USN on Contract No. NOw 61-0316-c (January 1-December 31, 1961); AD 273142. F-3-5-5

The recrystallization temperature of 2 internally oxidized Mo-1.5Ti alloys was determined. The alloy extruded with the lower reduction ratio of 4 to 1 had a recrystallization temperature of 2650 F, whereas the alloy extruded with a 6 to 1 ratio recrystallized at about 2400 F. Stress-rupture tests in argon at 2200 F of 3 internally oxidized alloys recrystallized during Dynapak extrusion gave lower properties than were obtained for stress-relieved arc cast Mo-1.5Ti.

Field, A. L., Jr., Ammon, R. L., et al., "Research and Development of Tantalum and Tungsten Base Alloys", Final Report No. 27, Westinghouse Electric Corporation, Pittsburgh, for USN on Contract No. NOa(s) 58-852-c (May 26, 1961); AD 259116. F-3-5-6

The effects of alloying upon the properties of tantalum and tungsten were examined. A 20-g button survey was made of the Ta-W-Hf and Ta-W-Re ternary systems to determine hardness, fabricability, oxidation resistance, and microstructure as a function of composition. The effects of substituting or adding titanium, zirconium, vanadium, columbium, and chromium into tantalum and tungsten-base alloys were also examined. A satisfactory technique was worked out for the melting and fabrication of tantalum-base alloys by arc melting from pressed and sintered electrodes and impact extruding at 1700 C with a Dynapak machine. The mechanical properties of the tantalum-base alloys were determined from -320 F to 3000 F on 50-mil sheet specimens. The alloys in general possess a remarkable combination of excellent low-temperature ductility and substantial high-temperature strength.

Cross References.

F-3-6-5 Discusses forging of refractory metals with a Dynapak machine.

F-3-7-1 Discusses forging and extrusion with a Dynapak machine.

Mechanical

Low Alloy Steels. F-3-6

Clark, D. S., and Wood, D. S., "The Tensile Impact Properties of Some Metals and Alloys", Transactions of the American Society for Metals, 42, 45-74 (1950). F-3-6-1

The results of tensile-impact tests in which force-time relations are determined can be placed on a rational basis through the concept of the theory of plastic-strain propagation. The theory of elastic- and plastic-strain propagation is reviewed in this paper.

Tensile-impact tests have been made on ingot iron, several plain carbon steels of different carbon content, several alloy steels, stainless steel (Type 302), copper, aluminum, two aluminum alloys, four magnesium alloys, and a zinc-base die-casting alloy. The influence of different heat treatments on the static- and tensile-impact properties of some of the steels is presented.

The ultimate strength, percentage elongation, and energy absorption under both static and dynamic conditions are presented graphically for all the materials. The critical velocity of these materials is defined and the experimental values are compared with the computed values of critical velocity. The results show that the ultimate tensile strength of all materials tested is greater under dynamic conditions than under static conditions. The advantages and disadvantages of a quench and temper treatment and an austemper treatment are presented from the standpoint of tensile-impact properties.

Maykut, A. R., "High Strain Rate Ausforming by Impact Extrusion", NAVORD Report 6964, NWPW-T-25-60 (January 9, 1961); AD 253803. F-3-6-2

The feasibility of using an impact extrusion technique for determining the influence of strain rate on the strengthening effect of ausforming was determined. A HY-GE actuator was used for the controlled impact extrusion of 4340 while at 1000 F. Although no strengthening effects were exhibited, this process shows promise as a means of investigating this phenomenon. The design of the punch and die assembly and the results of the trial run are presented.

LeGrand, Rupert, "Forging Tough Metals in One Blow", American Machinist/Metalworking Manufacturing, 105 (13), 72-73 (June 26, 1961). F-3-6-3

Some of the experimental work being conducted at American Brake Shoes, Mahwah, New Jersey, on a vertical 1810 Dynapak machine is discussed. Forgings of 4130 steel, tough-pitch copper, or copper powder compacts have been made on the new equipment. The machine is reported to have a maximum velocity of 150 feet per second and to be capable of exerting a force of 430,000 foot-pounds of energy.

Monahan, F. A., "Precision Forgings and Extrusions by the Dynapak Process", Machinery, 66 (10), 154-159 (June, 1960). F-3-6-4

The use of a Dynapak (pneumatic-mechanical device) at Convair is discussed. Draftless forgings of SAE 4130 steel have been produced with very good surface finish, requiring only a minimum amount of cleanup machining. Considerable cost savings have been reported for forgings and extrusions made by this device.

Monsees, Ralph G., "High-Energy Forming With a Machine Tool", Metal Progress, 76 (4), 111-113 (October, 1959). F-3-6-5

In this article a discussion of the applications of the Dynapak (pneumatic-mechanical device) is given. Some of the work which has been conducted on the forging of steel and refractory metals is presented. Powder compaction is also discussed.

Clark, D. S., Duwez, P. L., and Wood, D. S., "Influence of Impact Velocity on the Tensile Properties of NE-8715, NE 9415, SAE 1045, and SAE 1090 Steels", Progress Report No. 11 (NS-109), California Inst. of Technology, Pasadena, California (May, 1944); ATI 27463. F-3-6-6

This report gives the results of tensile-impact tests on NE 8715, NE 9415, SAE 1045, and SAE 1090 steels. Of the two carburizing steels the greatest energy absorbing capacity was found for the NE 9415 steel. For the particular heat treatment given to the SAE 1045 and SAE 1090 steels the former tends to have somewhat better energy-absorbing capacity than the latter. However, the spheroidized SAE 1090 steel has about the same energy absorbing capacity as the SAE 1045 steel spheroidized. The critical velocity of both spheroidized steels is about 110 feet per second which is the lowest obtained with any treatment.

Cross References.

E-2-39 Covers development of piston and cylinder arrangement for high-velocity, high-impact forming of steel.

K-1-19 Reveals inability of impact tests to indicate the true influence of strain rate on the tensile properties.

K-3-17 Investigates effects of rate of loading by controlled mechanical means on the yielding of mild steel.

## Mechanical

### Stainless Steels. F-3-7

Monahan, F. A., "Precision Forgings and Extrusions by the High-Energy-Rate Process", ASTME Technical Paper No. SP 60-21, presented at the Creative Manufacturing Seminars (1959-1960). F-3-7-1

A discussion of some of the forging and extrusion work which has been carried out at Convair on the Dynapak machine (a pneumatic-mechanical device) is given. Some of the materials which have been forged are 410 and 19-9DL stainless steel, 4340 steel, copper, and aluminum bronze. Tungsten has been extruded on this type of equipment at 3800 F. Some other materials which have been extruded are columbium, molybdenum, cast iron, titanium, superalloys, zirconium, and uranium. Development work is well under way in fabricating rifling in gun barrels and working ceramic and glass materials. Die materials found to be useful are the heat treated steels hardened to Rockwell C 47-50.

Some specific information on die design is also given.

"Forming With a Bang", Steel, 140 (23), 142 (June 10, 1957). F-3-7-2

High-velocity techniques are being used to form super tough metals like fully hard, Type 302 stainless steel. Convair has developed a high-velocity impact press called the Hyge (high-gee). It can deliver a 300,000 psi force. Impact force exceeds 1 million inch pounds. Closing velocity of the press is more than 200 feet per second. It is pneumatically operated with dry nitrogen at 1200 psi.

Cross References.

F-3-6-1 Gives results of tensile impact tests and describes changes in properties of stainless steels.

Mechanical

Titanium. F-3-8

Cross References.

E-2-39 Covers the development of piston and cylinder arrangement for high velocity-high impact forming of titanium.

Mechanical

Other. F-3-9

## Hardening

Explosive Contact G-1-0

"Plastic Deformation and Formation of Cracks by Detonating Charges", G-1-0-1
Ingen. Vetensk. Akad. Tidsk. Tekn. Forsk., 26, 16-25 (1955). In Swedish.

The author discusses the plastic deformation and some of the fractures which occur when an explosive charge is detonated in intimate contact with, or a high-velocity fragment strikes, a solid body. Several specific examples that have not been heretofore reported are described. Each example is accompanied by a brief description of the other investigations that are most likely to lead to an understanding of what has taken place in each case.

Cross References.

| | |
|---|---|
| B-4-28 | Gives dynamic theory for the explosive production of multiple shocks in metals which undergo phase transition. |
| B-4-29 | Analyzes explosive production of plane shock waves in solids. |
| B-4-30 | Analyzes explosive production of oblique waves in solids. |
| F-1-0-4 | Presents results of investigations in explosive hardening. |
| F-1-0-6 | Discusses explosive hardening of metals. |
| F-1-0-47 | Mentions explosive hardening in a general review of explosive forming. |
| J-1-3 | Discusses applications of explosives and propellants in hardening. |
| K-1-22 | Outlines preliminary considerations of deformation in strong shock and the accompanying structural changes. |
| K-1-24 | Gives behavior of metals under explosive forces. |
| K-2-5 | Discusses changes in microstructure and microhardness of chromium and nickel produced by high-intensity shock waves. |

Explosive Contact

Steel. G-1-1

Bertossa, R. C., "Explosive Forming and Chemical Milling Discussed", G-1-1-1
Metal Progress, 78 (3), 113-116 (September, 1960).

Explosive forming is covered in a general manner. Explosive hardening of austenitic stainless steels has yielded a hardness of Rockwell C-38 in plates up to 3 inches

thick. A discussion of fracture due to concentration and reflection of shock waves from a free surface provides information towards die design criteria. It was determined that shock waves moving out parallel to a face of the explosive are much greater than those moving at angles. This characteristic is useful in controlling local pressures, and also can be used in contour forming the more complex shapes.

Colgan, John E., and Wallace, Charles L., "Effect of Shock-Induced High Dynamic Pressures on Iron-Base Alloys", Quarterly Progress Rept. No. 1, Pratt and Whitney Aircraft, East Hartford, Connecticut, for USAF on Contract No. AF 33(616)8190, Proj. No. 1(8-7351) (June, 1961); AD 266619. G-1-1-2

The objective was to investigate the effect of high dynamic pressures generated by strong shock waves on the metallurgical properties of selected iron-base alloys. After the specimens were shocked, they were subjected to the tempering cycles which are optimum for the conventionally treated material and then examined for their mechanical and metallurgical properties. AISI H-11 steel realized an increase in yield strength from 215 ksi in the preshocked and untempered condition to 327 ksi in the postshocked condition with an accompanying decrease in the elongation from ten to six per cent. Light microscopy showed no apparent change in the microstructure after shocking.

Curran, D. R., Katz, S., Kelly, J. J., and Nicholsen, M. E., "Pressure Required for Transformation Twinning in Explosively Loaded Low Carbon Steel", Transactions AIME, 215 (1), 151-153 (February, 1959). G-1-1-3

The article describes work accomplished by explosively loading a wedge of 1020 steel. The pressure necessary for the alpha to gamma transformation was then calculated for iron. The pressure required was found to be 130 kilobars.

Dieter, G. E., "Hardening Effects Produced With Shock Waves", Seminar on Strengthening Mechanisms in Solids, ASM, Philadelphia, Pennsylvania (October 16, 1960). G-1-1-4

The general response of metals and alloys under very high strain-rate loading has been investigated. Grossly, only materials (iron and its alloys) that have a pressure-induced phase transformation show unusual behavior.

Harper, Wesely A., "Velocity Impact Hardening of Austenitic Manganese Steel", Taylor, Wharton Company, Easton, Pennsylvania. G-1-1-5

This article deals with explosive hardening of materials. Conventional hardening techniques are compared with velocity-impact hardening (VIH). The mechanism for VIH is given. VIH is not distinguishable from press- or hammer-hardened materials by metallographic techniques.

Harper, W. A., "Explosive Hardening of Steel Proves Out in Field Service", The Iron Age, 185 (5), 85-88 (February 4, 1960). G-1-1-6

This article shows that the use of high-energy-rate techniques on manganese steels has proved to be successful in extending the life of railroad rails. Parts so hardened have been in service three years with good results. The Du Pont hardening process using EL506 sheet explosive is used. Weldments and castings have been hardened with only slight changes in dimensions. The hardness-to-yield-strength ratio is less for explosively hardened materials than for normal work-hardened materials.

Harper, W. A., "Controlled Explosive Blasts Hardness Into Steel", Product Engineering, 30 (15), 62-63 (April 13, 1959). G-1-1-7

A new technique has been developed as a rival to the conventional methods of work-hardening castings made from high-manganese steel. The technique hardens the metal explosively but with a carefully controlled blow. There is practically none of the usual plastic deformation that occurs when hardening is accomplished by pressing or hammering. The relatively simple new method results in deeper hardening than that obtainable by cold deformation of the newly cast part or by cold working attained in service. The technique is called velocity-impact hardening (VIH). It is not the impact itself but the shock waves that do the work. They transform the soft, ductile austenite steel by stressing it internally, making it strong, tough, and wear resistant. The material is microscopically indistinguishable from the product obtained by cold working method.

Hollis, W. S., "Explosive Forming", Aircraft Production, 22 (12), 446-451 (December, 1960). G-1-1-8

Photomicrographs of sections from several sources show that the effect of adiabatic straining, as in explosive forming, is to produce a fine and diffuse slip in preference to the coarse slip exhibited at low rates of deformation. In precipitation-hardening steels, martensitic banding also appears to be a feature of high strain-rate. It was found that large strains applied adiabatically seem not to produce the work-hardening experienced when deforming at lower rates. This argument is used to explain why some materials behave in a more ductile manner under high-velocity deformation.

No experimental work is described although a considerable amount of general information on all of the various energy sources is given.

Holtzman, A. H., and Cowan, G. R., "The Strengthening of Austenitic Manganese Steel by Plane Shock Waves", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), p 447-482. G-1-1-9

Specimens of austenitic manganese steel were subjected to shock action in an arrangement which produced uniaxial compression in a shock front followed by essentially uniaxial expansion in a plane rarefaction wave moving in the shock direction. Passage of the wave causes a marked strengthening which increases with shock

pressures in the range studied, from 70 to 422 kbars. A 422 kilobar shock changes the mechanical properties as follows: from 158,000 to 174,000 psi yield strength; from 134,000 to 224,000 psi tensile strength; from 60 to 19 per cent elongation; and from 208 to 580 Dphn. In comparison with material cold rolled to the same tensile strength, shocked austenitic manganese steel has appreciably higher ductility.

A 70 kilobar shock wave produces microstructural markings which are very similar to the markings found in cold-rolled austenitic manganese steel.

LaRocca, E. W., "Unique Structure of Pearlite Deformed by Explosive Loading", Acta Metallurgia, 5 (7), 408-410 (1957). G-1-1-10

This article covers some investigation on shock deformed pearlite in 1020 steel. Photomicrographs are shown of a pearlite grain where the lamellae of cemetite have been displaced in multiple steps as though the grain had received successive impacts. It is believed that the stepped structure is a result of shock twins in the ferrite matrix, the shock being transmitted through the cemetite.

MacLeod, Norman A., "Method of Hardening Manganese Steel", U. S. Patent No. 2,703,297 (March 26, 1951). G-1-1-11

This patent relates to methods for hardening manganese steel by explosive means. It covers hardening in air or under heavier media such as water.

Pearson, John, and Rinehart, John S., "Hardness Plateaus and Twinning in Explosively Loaded Mild Steel", Journal of Applied Physics, 25 (6), 778-781 (June, 1954). G-1-1-12

Hardness measurements were made along radii of circular cross sections of an annealed thick-walled low-carbon steel cylinder internally loaded with an explosive charge. The degree of work hardening in the cylinder wall was found to decrease non-uniformly with an increase in distance from the surface in contact with the explosive. Each hardness-versus-distance curve exhibited a series of plateaus along which the hardness remained constant. The plateaus appear to be related to Neumann bands which are present in the steel. The maximum number of twin directions in a single grain increases with the magnitude of the stress. The presence of the hardness plateaus and the increase in the number of twin directions with hardness and stress level point to the existence of critical stresses for twinning.

Rinehart, John S., "Work-Hardening of Mild Steel by Explosive Attack", Journal of Applied Physics, 22, 1086-1087 (1951). G-1-1-13

Rapid absorption of the high-intensity compressional-stress wave that is generated in a steel plate by application of an explosive charge has been established. Appearance of at least part of this energy in the form of cold working of the metal is to be expected. Since the initial stress is extremely high, about 300,000 atmospheres, and of very short duration, two or three microseconds, it is of considerable interest to observe the character of the work hardening that takes place. The fact that the wave is

attenuated as it passes through the steel permits observations to be made at varying stress levels. The data and observations presented are consistent in general with the view that more or less normal plastic flow, i.e., slip, grain breakdown, etc., superimposed on shock twinning accounts for the increased hardness in the narrow region close to the explosive, and that shock-twinning is mainly responsible for the increase in hardness throughout the rest of the plate.

Rinehart, J. S., "Some Experimental Indications of the Stresses Produced in a Body by an Exploding Charge", Journal of Applied Physics, 22, 1178-1181 (1951). G-1-1-14

The effects of detonating explosive charges on the surface of heavy steel plates is discussed. The mechanism of failure is discussed and stress distribution is determined by conducting a hardness survey after the plate is sectioned. Experimental techniques are not discussed.

Zukas, E. G., and Fowler, C. M., "The Behavior of Iron and Steel Under Impulsive Loading", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), p 343-369. G-1-1-15

The behavior of iron under plane shock-wave loading at pressures from 45 to 750 kbars, and the effect of prestraining by rolling or pressing on this behavior are discussed. In annealed iron, Neumann bands (mechanical twins) are normally formed by shock loading, and appear to be formed principally by action of the elastic pressure wave. Shock pressures above 130 kbars produce a polymorphic transformation in iron. Iron which has undergone this transformation, when unloaded and cooled rapidly to atmospheric temperatures, returns to essentially its original condition without evident changes in crystal orientation or destruction of previously formed Neumann bands.

Explosive Impact Hardening for Metals, E. I. du Pont de Nemours and Company, Incorporated, Wilmington, Delaware. G-1-1-16

This brochure discusses the application of sheet explosive for the impact hardening of manganese austenitic steel (12-14 per cent Mn). The use of explosive-hardening techniques has demonstrated better through hardening characteristics than is available by conventional working of the surface. Curves are presented indicating the effects of multiple impacts on the hardness depth profile of the material. Some information is also presented on the effects of explosive hardening on the mechanical properties of 302, 304, and 316 stainless steels.

"Explosive Hardened Manganese Steel – A New Kind of Austenitic Steel", Engineering and Mining Journal, 160 (1), 47 (January, 1956). G-1-1-17

Greater depth of hardening is realized with explosive hardening – 1-2 inches – as compared to 1/20 inch obtained by shot peening. The hardness is usually increased from 220 Brinell in the as-cast and heat-treated condition, to 400 Brinell in the explosive hardened condition. The tensile and yield strengths are thought to be

approximately doubled and quadrupled at these hardnesses, respectively. The explosive loading and number of times the pieces are impacted have been found to effect both the surface hardness and the depth of the hardened zone. According to the MacLeod patent, shooting underwater is an advantage, but Du Pont believes that this is not necessary except in conjested areas where noise may be objectionable.

"This Part is Hardened With Explosives", Steel, 144 (18), 84-85 (May 4, 1959). G-1-1-18

This article discusses explosive hardening of austenitic-manganese (Hadfield) steel parts. Hardness is increased 300 Brinell points (up to 55 Rockwell-C); tensile strength is doubled; yield strength is quadrupled. Explosive hardening effects penetrate 2 inches as compared with shot peening which penetrates 0.050 inch.

Hardening is done with Du Pont EL 506A, a sheet explosive.

LaRocca, E. W., "Phase Transformation in the Microstructures of Explosively Loaded Iron and Steel", Physical Review, 100 (6), 1800 (December 15, 1955). G-1-1-19

By subjecting annealed low-carbon steel and commercially pure iron to explosive loadings, structures resembling martensite are induced in the materials. The structure, which is of a Widmanstatten form, is most noticeable in Armco iron. X-ray-diffraction studies show no residual phases other than alpha iron present after impulsive loading, but the microstructure indicates a phase change has occurred (locally) with alpha iron reforming along the octahedral planes of the gamma phase.

Silverman, Steven M., Godfrey, Loren, Hauser, Allen H., and Seaward, Edward T., "The Effect of Shock Induced High Dynamic Pressures on Iron-Base Alloys", ASD-TDR-62-442, Pratt and Whitney Aircraft Division, United Aircraft Corporation, for USAF on Contract No. AF 33(616)-8190 (August, 1962). G-1-1-20

The object of this program was to investigate the effect of high dynamic pressures generated by strong shock waves on the metallurgical properties of selected iron base alloys. This investigation included a study of the effects of shock wave duration, repeated shocks on a single test specimen, increasing shock wave intensity and post shock treatment on the yield and tensile strengths of H-11 tool steel and 25 per cent Ni steel. As a result of explosive shock hardening, H-11 steel increased in yield strength from 235 ksi in the preshock condition to 340 ksi in the as-shocked 360 kilobars condition The 25 per cent Ni steel showed yield strength increases from 235 ksi in an austenitized-plus-aged condition to 255 ksi in the shocked-plus-aged condition. These increases in yield strength were brought about without any significant microscopic plastic deformation.

Cross References.

B-4-26 Discusses abrupt changes of pressure caused by compressive waves generated by high explosives and how these are consistent with the hypothesis of polymeric transition in iron.

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|---|---|
| F-1-0-71 | Reports on explosive hardening of austenitic steels. |
| K-1-21 | Gives technique to measure pressure and density as a function of distance from the explosion. |
| K-1-26 | Describes influence of impact velocity on tensile properties of plain carbon steels. |
| K-1-27 | Describes effect of impact velocity on the tensile properties of sheet steel. |
| K-1-42 | Describes generation of shock waves in mild steel at different temperatures by explosives. |
| K-1-43 | Discusses plastic deformation caused by explosives in intimate contact with metal. |
| K-1-54 | Presents dynamic shock properties of various iron alloys. |
| K-2-2 | Compares coarse slip (occurs at normal strain rates) with fine slip (occurs at high strain rates) in medium carbon steel. |
| K-2-6 | Discusses phase transition in iron caused by shock waves. |
| K-3-3 | Reviews high strain rates and the effect on twinning in softer steels. |

Explosive Contact

Other. G-1-2

Walsh, J. M., Rice, M. H., McQueen, R. G., and Yarger, F. L., "Shock Wave Compressions of Twenty-Seven Metals Equations of State of Metals", Physical Review, 108 (1), 196-216 (1957). G-1-2-1

An explosive system is used to drive a strong shock wave into a plate of 24ST aluminum. This shock wave propagates through the 24ST aluminum into small test specimens which are in contact with the front surface of the plate. A photographic technique is used to measure velocities associated with the 24ST aluminum shock wave and with the shock wave in each specimen. Resulting pressure-compression curves are given for 27 metals. The pressure interval is 150 to 400 kilobars. Very detailed information on the various metal behaviors is given.

Walsh, J. M., and Christian, R. H., "Equation of State of Metals From Shock Wave Measurements", Physical Review, 97, (6), 1544-1556 (March 15, 1955). G-1-2-2

Pressure magnitudes of from 150 to 500 kilobars were applied to metals with high explosives. Free surface velocities were determined by photographing the movement of shock waves in air or argon due to the pressure wave in the material. Results are analyzed and techniques are described.

Krupnikov, K. K., Brazhnik, M. I., and Krupnikova, V. P., "Shock Compression of Porous Tungsten", Journal of Experimental and Theoretical Physics (USSR), 42 (3), 675-685 (March, 1962). Translation in Soviet Physics Jetp, 15 (3), 470-476 (September, 1962). G-1-2-3

Parameters of strong shock waves in tungsten samples of various initial densities were investigated experimentally. Shock adiabats with negative slopes in pressure-density coordinates were found for porous samples at pressures below $0.5 \times 10^6$ atmospheres. Bending of the adiabats and a change in sign of their derivatives were observed with increase of the shock-wave amplitude. This behavior of adiabats is accounted for by changes in dependence of the effective Grueisen constant on the degree of compression and heating due principally to the increase in the electronic specific heat. Expressions are derived relating the partial derivatives $(\partial E/\partial P)_v$ and $(\partial E/\partial v)_p$, with the slopes of two intersecting curves.

Hughes, D. S., Gourley, L. E., and Gourley, Mary F., "Shock Wave Compression of Iron and Bismuth", Journal of Applied Physics, 32 (4), 624-629 (April 4, 1961). G-1-2-4

A helium gun was used to propel metal projectiles against targets of the same materials. Pressures produced by impact were varied by varying projectile velocity. The method produced pressures up to somewhat over 100 kilobars thus overlapping the lower part of the range of pressures which can be produced by detonation of high explosives. Of particular interest was the range of pressures immediately between the highest which can be produced statistically and the lowest which can be produced explosively. A condenser micrometer was used to detect motion of the free surface of the target. This method permitted examination of the motion in greater detail and could reasonably be accomplished by other methods which have been used. Elastic and plastic waves were observed in iron and in bismuth. Assuming the ranking Hugonoit shock conditions, pressures and compressions were computed. Pressure-compression data for iron were obtained for intermediate pressures not previously investigated. Phase transitions in bismuth were observed for pressures up to about 40 kilobars.

Hall, A. W., Matsuda, T., Hendriksen, E. K., and Wagner, M. H., "Investigation of the Effect of High Dynamic Pressures Upon the Metallurgical Properties of Iron and Titanium Base Alloys", 0485-01-(02)QP, Aerojet-General Corporation, Downey, California, for USAF on Contract No. AF 33(616)-8191 (October 24, 1961); AD 265365. G-1-2-5

The objective of this program is to investigate the effect of high dynamic pressures upon the metallurgical properties of iron and titanium base alloys. The explosive system adopted for use for generating the high dynamic pressures against test specimens was modified for a device used on previous work. The effects of high dynamic pressures on the metallurgical properties of AISI 1020 steel specimens are demonstrated by an appreciable increase in surface hardness and metallurgical changes in grain structure. High-density-deformation twins are shown as a result of the dynamic pressures. A chevron pattern with alternating bands of high- and low-deformation twins is observed.

Cross References.

| | |
|---|---|
| E-2-20 | Gives results of high-speed compression tests on copper in terms of energy absorbed versus deformation. |
| E-2-29 | Summarizes progress in use of pin technique to determine the free surface velocity of aluminum. |
| G-1-1-8 | Explains why some materials are more ductile after high-velocity deformation. |
| K-0-14 | Describes electrical measurement of the shock and free surface velocity in a plate of 24St aluminum alloy. |
| K-1-28 | Summarizes the influence of impact velocity on the tensile properties of 24 ferrous and 12 nonferrous alloys. |
| K-1-35 | Shows where deformation takes place in single crystals of aluminum and copper. |
| K-1-42 | Describes generation of shock waves in copper at different temperatures using explosives. |
| K-1-44 | Describes use of plastic and elastic stress wave propagation to analyze the dynamic stress-strain relations for aluminum. |
| K-1-55 | Studies deformation of aluminum under impulsive loads of equal maximum stress but different impulses. |
| K-1-56 | Studies deformation of copper under different impulsive loads. |
| K-1-60 | Discusses deformation of a single crystal of pure aluminum caused by explosives. |
| K-2-10 | Shows slip and kink bands in copper are not associated with initial intense compression but come later. |
| K-2-11 | Describes X-ray diffraction examination of explosively loaded copper; found kink bands but no macrotwins. |
| K-2-13 | Develops certain crystallographic aspects of deformation as a function of velocity. |
| K-3-19 | Computes ratios for the compressional and shearing strains at the shock fronts in a magnesium alloy. |
| H-7-2 | Describes hardening of copper plates with explosives. |

## Explosive Welding

Davenport, Donald E., and Duvall, G. E., "Explosive Welding", ASTME Report No. SP 60-161, Presented at Creative Manufacturing Seminars (1960-1961). H-0-1

This paper describes the research work which has been performed at the Stanford Research Institute on explosive welding. To obtain diffusion welding it is normally necessary to have very smooth and ultraclean surfaces. It was therefore believed that the forces involved in explosive welding would be sufficient to give the intimate contact required and to break up surface films without the requirements for very smooth or clean surfaces. It is shown that there are applications for the process in the field of cladding.

Pearson, John S., "Navy Expert Outlines ABC's of Explosive Metalworking", Steel, 146 (12), 140-143 (March 21, 1960). H-0-2

This article covers the fundamentals of the explosive-metalworking process, the operations that are feasible today, and the influence of explosive charges on the materials being worked. The four possible systems for explosive welding are described. It is now believed that an increase in the percentage of stretch is possible with some metals, and, with the speeded-up forming, an increase in yield and ultimate strength is possible. Some of the areas covered are forming, powder compaction, and welding.

Pearson, John, "Explosive Welding", ASTME Report No. SP 60-159, presented at Creative Manufacturing Seminars (1960-1961). H-0-3

This paper describes the work which has been conducted on an experimental basis in the field of explosive welding. The operation consists of the use of high pressures from explosive charges for impulsive bonding. The plastic interaction which occurs between the structures of adjacent metal parts when they are subjected to a variety of explosive-welding techniques effects the bonding mechanism. It has been found that the degree of plastic interaction appears to depend on the inherent ductility in the component pieces. Information on the mechanisms of this technique, dynamics of the operation, and characteristics of the joints obtained are given.

Zernow, L., Lieberman, I., and Kincheloe, W. L., "Welding and Joining New Applications of Explosives", The Tool and Manufacturing Engineer, 47 (1), 75-78 (July, 1961). H-0-4

The theory of explosive welding is discussed. Welds are obtained by either subjecting the bond interface to a very high normal force or by causing a sudden shear between the two surfaces under pressure. By driving two pieces of material together both of the above conditions are obtained. The important factor which must be controlled in explosive welding is the critical velocity of different materials so that there is an overlap in the range if dissimilar materials are to be welded. The angle of approach of the two materials is also important. Very little specific data are available on the controlling parameters of the process.

Explosive joining utilizes the mechanical connection between two members which has been formed in such a manner as to provide locking between the members. This process depends on the coefficient of friction between the members on and the shape of formed grooves or surface indentions. Its best application would be in the field joining of large tubing members for mechanical strength only.

"Explosive Welding, Forging Still Viewed as Too Costly", American Metal Market, 16 (May 24, 1961). H-0-5

This article is an editorial reporting on a presentation at the American Society of Tool and Manufacturing Engineers by Mr. Philipchuk of American Potash and Chemical Corporation.

"Explosive Welding is on the Way", Steel, 145 (18), 90-91 (November 2, 1959). H-0-6

This article describes work being performed at National Northern by Philipchuk and at China Lake by John Pearson on explosive welding of various materials and combinations. A general description of the method used is given. No specific data are reported.

Rieppel, P. J., "Metals Joining Processes", Machine Design, 32 (12), 189-196 (June 9, 1960). H-0-7

The article deals with the latest developments in welding, and the last section with explosive welding. It merely mentions that the process is in its infancy, and that indications from the data reported are that different metals require different techniques.

Wilson, W. C., "Explosive Bonding Gains Ground Through Simplified Setups", Iron Age, 189 (22), 127-129 (May 31, 1962). H-0-8

The author describes the work being done at General Dynamics/Astronautics in the field of metals joining – especially dissimilar refractory metals, by explosive means. By leaving an air gap between the two metals, the detonation of the explosive compresses this air and generates enough heat to fuse the metals together. He goes on to describe the setup for the welding operation and, finally, gives results which were obtained. There is a photomicrograph included in the article which shows two pieces of aluminum which were fused so tightly that there is no visible interface.

"Explosive Welding", Machinery, 100 (2587), 1350-1351 (June 13, 1962). H-0-9

The investigations made at Stanford Research Center in explosive welding are discussed. The method used for welding and what actually happens to the metal is described.

Boes, P. J. M., "Some Aspects of Explosive Welding", Paper presented at the Twelfth General Assembly of CIRP, The Hague, September, 1962, Technical Centre for Metalworking, Metal Research Institute (TNO), Delft, Holland. H-0-10

A survey is given of investigations carried out by the Technical Centre for Metalworking on the subject of explosive welding of different materials. The setup and equipment used by the Centre for explosive welding are described and compared with those described in literature. The processes involved in explosive welding are not yet very well known. Explanations offered by Davenport, Philipchuk, Pearson and Holtzman, and Rudershauer are evaluated. A new theory is advanced by the Centre partly based on the findings of the Centre and partly on those of the authors mentioned above. The properties of the welds are of primary importance. Tests have been carried out on the tensile and shear strength of welds between different materials. Structures found in the welds have been carefully investigated partly in close cooperation with Dr. Verbraak, Department of Applied Fundamental Metals Research of the Metal Research Institute, TNO. The use of an intermetallic layer between the surfaces to be welded, in particular, when welding different materials is discussed. The results of the application of such a layer are shown.

Cross References.

F-1-0-4 Results of investigations in explosive welding.

F-1-0-6 Discusses explosive welding of metals.

F-1-0-33 General review of present uses of explosives in the metalworking field, including explosive welding.

F-1-0-34 Mentions use of explosives for high-speed welding.

F-1-0-91 Discusses experimental work in explosive welding at Aerojet.

F-1-1-14 Discusses explosive welding techniques.

F-1-5-4 Covers explosive welding operations in one organization.

## Explosive Welding

### Aluminum H-1

Davenport, Donald E., "Explosive Welding", ASTME Report SP 62-77, Presented at the Creative Manufacturing Seminars (1961-1962). H-1-1

The general principles of explosive welding are presented based on work with the Al-Al weld. Shear tests and peel tests of the welds indicate that they can be stronger than the parent metal. Photomicrographs have been obtained of a wide variety of other

metals which have been explosively welded including copper, steel, titanium, niobium, molybdenum, and tantalum. Examination of several of the copper welds indicates evidence of diffusion at the interface. The implied diffusion rates are unbelievably great, but satisfactory alternative explanations have not been developed.

"How Explosives Weld Metals", The Iron Age, 187 (18), 83-85 (May 4, 1961). H-1-2

The explosively welded systems studied in this report were aluminum to aluminum, stainless steel to stainless steel and nickel alloys, and copper to copper. Explosive welding shows promise for use with reactive and refractory metals.

The behavior of a system depends on a number of parameters, including plate thickness, explosive thickness, the included angle B, and the length and width of the system. Other variables include the type of explosive, metal properties, and the effect of a buffer material.

"Explosive Welding of Aluminum", Light Metal Age, 19 (3-4), 6-9 (April, 1962). H-1-3

The article discusses some of the experimental work being carried out by Donald Davenport and G. E. Duvall on explosive welding. Aluminum-to-aluminum, aluminum-to-copper, and copper-to-steel welds have been made. Vacuum requirements of from 1/10 to 1 mm of mercury have been found to be sufficient for the welding of aluminum. The use of the vacuum reduces the closing velocity required from 3,000 fps to 500 fps for aluminum and to 1,200 fps for steel. EL506 sheet explosive has been used as the explosive. Welding was found at approximately 350,000 psi for copper against copper and 90,000 psi for aluminum against aluminum (400 feet per second and 750 feet per second, respectively). When welding materials with tightly-adherent-oxide coatings it was found that fresh metal is exposed by means of interfacial working. This indicates the possibility of welding unprepared specimens.

Cross References.

H-7-1 Gives specific information on explosive welding of aluminum in Canada.

K-1-31 Mentions explosive welding of aluminum to aluminum, aluminum to Inconel, and aluminum to stainless steel.

## Explosive Welding

### Copper H-2

Cross References.

H-1-1 Presents general principles of explosive welding. Includes photomicrographs of copper welds.

H-1-2 Reports on copper-to-copper explosive welds.

H-1-3 Discusses explosive welding of copper to aluminum and copper to steel.

H-7-1 Gives specific information about work done in Canada on explosive welding of copper.

Explosive Welding

Magnesium H-3

Explosive Welding

Nickel H-4

Cross Reference.

H-1-2 Reports on welding stainless steel to nickel alloys.

Explosive Welding

Refractory Metals H-5

Cross Reference.

H-1-1 Presents general principles of explosive welding. Includes photomicrographs of refractory metal welds.

Explosive Welding

Low Alloy Steels H-6

Philipchuk, Vasil, "Explosive Welding", ASD Technical Report 61-124, American Potash and Chemical Corporation for USAF on Contract No. AF 33(616)-6797, Project 7351, Task 73516 (August, 1961). H-6-1

Methods were developed for the successful welding of 4340 steel to 4340 steel, 6Al-4V titanium to 6Al-4V titanium, and molybdenum to 310 stainless steel by the use of explosive forces. No success was achieved with B120 VCA titanium to B120 VCA titanium and molybdenum to molybdenum. Test specimens were in sheet or strip form. All welds were lap type, with one piece of metal directly over or lapped over the other. Successful welds of the above three metal combinations indicate that explosive forces

can be utilized for lap weldments of sheet metals when the proper test parameters and techniques have been investigated and developed.

Cross References.

F-1-6-7 Describes explosive welding of steel sheets.

H-1-3 Discusses explosive welding of steel to copper.

## Explosive Welding

### Stainless Steels H-7

Tardif, H. P., "Explosive Forming in Canada", Metal Progress, 17 (1), 128-130 (January, 1960). H-7-1

This article presents the development work being conducted in Canada on explosive forming. Explosive forming is covered in a general manner while work conducted on explosive welding is treated in more detail. Tests were made on different combinations of stainless steel, aluminum, brass, and copper. Metallographic examination indicates new phases are formed with the lowest melting constituent being the base metal. Methods for forming cones are shown wherein the walls are thickened over the thickness of the original blank.

"Researches Score Three Bull's Eyes in Explosive Metalworking", Steel, 147 (16), 126-128 (October 17, 1960). H-7-2

Tells of work at Battelle Memorial Institute by Charles Simons and Stanley Porembka in explosive metalworking. They corrugated and sized metal tubes containing extremely brittle cermet cores. They put stainless cladding on stainless ceramic tubes in a single blast. They hardened copper plates from Rb 20 to Rb 100 without fracturing the metal. The article describes how they performed each of these operations.

Cross References.

H-1-2 Reports on welds of stainless steel to nickel alloys.

H-6-1 Gives methods for explosive welding molybdenum to AISI 310 stainless steel.

K-1-31 Mentions explosive welding of stainless steel to aluminum and stainless steel to itself.

## Explosive Welding

**Titanium** H-8

Cross References.

H-1-1 Presents general principles of explosive welding. Includes photomicrographs of titanium welds.

H-6-1 Gives method for explosive welding titanium to itself.

## Explosive Welding

**Other** H-9

Allen, A., Mapes, M., and Wilson, W. G., "An Effect Produced by Oblique Impact of a Cylinder on a Thin Target", Journal of Applied Physics, 25 (5), 675 (May, 1954). H-9-1

A discussion of the results of firing steel cylinders into thin lead plates is given. If the striking angle is less than a certain critical angle the front of the cylinder is plastically deformed to a negligible degree. If the angle is greater than the critical angle, the front of the cylinder is marked by a series of ridges, the spacing of which depends upon the thickness of the plate.

## Powder Compaction

Cross, A., "Try Hot Explosive Compacting for Sintered Powder Products", Iron Age, 184 (26), 48-50 (December 24, 1959). I-0-1

A new explosive-forming technique produces powder compacts in sintered conditions. Among its advantages are: ability to form materials with a minimum of springback; cheap processing of large sections since forming presses are eliminated; and forming of difficult shapes such as bulges or necks in tubes. Explosive forming also appears to offer a handy answer to the problem of consolidating metal powders into forms too hard, or impossible, to make by normal techniques.

Cross References.

F-1-0-6 Discusses compaction of metal powders by explosives.

F-1-0-47 Reviews explosive forming and reports on pressing of powders.

F-1-0-54 Covers use of explosive charges for compaction.

J-2-7 Mentions using explosives for powder compaction.

## Powder Compaction

### Explosive Compaction I-1

Mason, P., "High-Speed Fracture in Rubber", Journal of Applied Physics, 29 (8), 1146-1150 (1958). I-1-1

Small explosively-activated presses have been used as research tools in the study of the behavior of powdered materials under impulsive loads. The double-action press, which is of sandwich-type construction, uses two explosive charges fired simultaneously to drive two opposed pistons together into a central steel cylinder in which the specimen material has been placed. By modifying the working faces of the pistons, materials can be formed into various shapes by the action of the press.

LaRocca, E. W., "Making Compacts by Explosive Forming", Metal Progress, 76 (3), 85-86 (September, 1959). I-1-2

A double-acting explosive press for compacting powders is described and its operation is discussed. Compacts from sponge cobalt, coarse titanium filings, and solid graphite disks have been prepared. The cobalt sample was compressed to a homogeneous disk 0.012 inch thick. After forming, the density of the titanium compact was only five per cent less than that of the original bar from which the filings were obtained. The graphite workpiece was a solid disk, 1/16 inch thick, machined from a 1/2-inch-diameter bar. Compression increased its diameter and density without cracking it.

Paprocki, S. J., Simons, C., and Carlson, R. J., "Explosive Compaction of Powder Materials", ASTME Technical Paper No. SP 62-29, Presented at Creative Manufacturing Seminars (1961-1962). I-1-3

On the basis of several years of experimentation, the use of explosive energy to compact powder materials may well develop into its most important application to materials technology.

Compacting procedures are discussed. In the majority of cases, densities of 94 to 96 per cent of theoretical, as determined by pycrometer methods, and excellent green strengths have been achieved. A representative sample of the data obtained during this work is given.

Pearson, John, "Explosive Compaction of Powders", ASTME Report No. SP 60-158, Presented at Creative Manufacturing Seminars (1961-1962). I-1-4

Work which has been conducted at the China Lake U. S. Naval Ordnance Test Station on the explosive compaction of powders is presented. The initial work was with expendable explosively activated presses. More recent work has indicated that, in addition to use as a research tool, the explosively-activated-press concept may lend

itself to numerous industrial applications. The high density compacting of powders, the forming of parts, and the bonding together of dissimilar materials are some of the interesting possibilities. Very high densities have been obtained in powders, approaching the theoretical densities of the materials.

Porembka, S. W., and Simons, C. C., "Compacting Metal Powders With Explosives", ASTME Report No. SP 60-102, Presented at Creative Manufacturing Seminars (1960-1961). I-1-5

The two basic methods of explosive compaction of the press type are discussed. The advantages and disadvantages of each system are given and some of the experimental work which has been conducted on the compaction of various powders is presented.

"Try Hot Explosive-Compacting for Sintered Powder Products", Iron Age, 184 (26), 48 (December 24, 1959). I-1-6

A new explosive-forming technique produces powder compacts in a sintered condition. The key to the process is compacting of metal above its recrystallization temperature. The technique forms materials with properties better than those obtained with the normal compaction and sintering process.

"Explosives to Form Tungsten", Product Engineering, 29 (4), 12 (January 27, 1958). I-1-7

This article reveals the prediction of a Russian metallurgist, Pokrovsky, that tungsten and molybdenum bar and pipe will be formed by feeding continuous explosive into a chamber lined with metal powder. "Explosion forces will sinter the metal and produce a bar or pipe of desired size."

McKenna, P. M., Redmond, J. C., and Smith, E. M., "Process for the Explosive Pressing of Powdered Compositions", U. S. Patent No. 2,648,125 (August 11, 1953). I-1-8

In this invention, the metal powder to be pressed is placed in a sealed bag and immersed in a liquid. At one end of the tank containing the liquid is a piston behind which is an explosive charge. When the explosive is detonated it activates the piston which is forced against the liquid. The liquid transfers the pressure to the metal powder and compacts it.

LaRocca, E. W., and Pearson, J., "High Pressure Explosive Activated Press", U. S. Patent No. 2,948,923 (August 16, 1960). I-1-9

This apparatus is designed to provide very high pressures with high rates of deformation of the material pressed. The material is compressed by a piston which is driven by an explosive.

Cross References.

F-1-0-33 Reviews uses of explosives in metalworking, including compaction of powder metal.

F-1-0-34 Mentions use of explosives for compacting metal powders.

F-1-0-91 Discusses powder compaction with explosives at Aerojet-General Corporation.

F-1-0-99 Covers field of explosive powder compaction in detail.

F-1-5-4 Describes explosive compaction of metal powders at one organization.

J-1-3 Discusses applications of explosives in powder compaction.

## Powder Compaction

### Mechanical Compaction I-2

Cross References.

F-3-6-3 Discusses compaction of copper powder with a Dynapak machine.

F-3-6-5 Discusses powder compaction with a Dynapak machine.

## Metal Removal

Cross References.

F-1-0-34 Mentions use of explosives for controlled cutting.

F-1-0-54 Covers use of explosive charges for perforation.

F-1-0-74 Discusses work on metal fracturing and cutting with explosives.

F-1-8-6 Reports blanking of titanium sheet using dynamite.

K-0-77 Considers perforation of thin plates by high-speed projectiles from a momentum viewpoint.

## Metal Removal

### Machining J-1

Vaughn, Robert L., "Ultra-High-Speed Machining: Solution to Producibility Problems", The Tool Engineer, 41 (4), 71-76 (October, 1958). J-1-1

Machining variables, reasons for metal failure, plastic deformation, the potentialities of ultra-high-speed machining, and explosive forming as applied to the new high-temperature metals are discussed.

Vaughn, Robert L., Peterson, Alfred H., et al., "Ultra-High-Speed Machining", Interim Engineering Report No. 4, LR-13595, Lockheed Aircraft Corporation, Burbank, California, for USAF on Contract No. AF 33(600)-36232, December 1, 1958-February 28, 1959; AD 203700. J-1-2

This contract investigates the feasibility of applying ultra high speed machining to high strength materials. This report describes the development and checkout of specialized test apparatus. Techniques for measurement of cutting velocities, temperatures, and forces are discussed. Reproductions of chip formation photography and metallographic analyses of test specimens are presented.

Vensel, H., "Explosive Fabrication", Metal Industry, 94 (24), 481-482 (June 12, 1959). J-1-3

Some of the applications of explosives and propellants are discussed in forming, hardening, cutting, and powder compaction. The information is general in nature. The cutting action of a 3/8-inch-square tool bit ejected from a gun at surface speeds up to 180,000 surface feet per minute is discussed.

"High-Energy Working", Aircraft Production, 23 (9), 312-315 (September, 1961). J-1-4

The use of heated dies in the explosive forming operation has produced titanium hemispherical shapes at 1200 F. With 0.1075-inch-thick material the maximum thinning was found to not exceed 0.007 inch. The production of 30-feet-diameter domes for missiles by welding explosively formed segments into a conical frustrum is discussed.

Some of the work conducted on high-velocity machining is discussed. The materials investigated were 4340 steel, 350 stainless steel, Inconel X, 6Al-4V titanium, and 7075-T6 aluminum alloy. A cutting velocity of 120,000 surface feet per minute was best, in the conditions imposed for the 4340 steel. Minimum tool-wear occurred at this speed. Increasing cutting speeds in a ratio of 5,000:1 produced equal or less wear on the high-speed-steel tool bit. There was no measurable tool wear when 7075-T6 aluminum alloy was machined at 120,600 feet per minute. Surface finishes for all metals tested ranged from 3-99 microinches with no significant variation due to cutting speeds.

## Metal Removal

### Shaped Charge Cutting J-2

Clifford, J. E., Semones, D. E., and McCallum, J., "High-Temperature-Alloy Cutting Program", Final Engineering Report AMC TR-59-7-617, Battelle Memorial Institute, Columbus, for USAF on Contract No. AF 33(600)-35440 (January, 1959); AD 210979. J-2-1

New methods for cutting high-temperature alloys have been investigated. The new methods included chemical machining, chemical cutting by high-velocity jets, abrasive slurries, ultrasonics, electroarc and electrospark machining, explosive cutting, and electrolytic machining. Multiple cutoff by electrolytic machining was selected for development. A survey was made of presently used industrial methods for billet cutoff. This survey permitted economic comparisons of new with existing methods and pin-pointed the important specifications for industrial cutoff. The most important conclusion was that the cost and time for cutting can be insignificant compared with the cost and time for handling materials before and after the cuts. For this reason multiple cutting was deemed to be the best way for a faster, more economic method of cutoff. Multiple cutoff requires substantially no tool wear, and electrolytic cutting appears to be the best way to meet this specification. Another important conclusion was that kerf loss becomes a major cost item for the cutoff of titanium and other expensive high-temperature alloys. Electrolytic cutoff appeared to offer the best prospect for minimum kerf loss.

Gardiner, J. T., "Use of Shaped Charge Process for Open Hole Shooting", World Oil, 131 (3), 99-103 (August, 1950). J-2-2

This article deals with the use of shaped charges in oil-well drilling.

Moses, S. A., and Huber, G. B., "Fundamental Studies of Explosive Charges", Steel Cutting Charges, Vol 1, Final Report, Poulter Labs, Stanford Research Institute, Menlo Park, California, to USA on Contract No. DA 44-009-Eng-2512 (April 15, 1957); AD 140872. J-2-3

A theoretical discussion of the cutting of metals with explosives is given and the application of the theory to the cutting of steel bars and cables is discussed. New types of shaped charges for cutting are described.

Pearson, John, "Metal Cutting With Explosives", ASTME Report No. SP 60-160, Presented at Creative Manufacturing Seminars (1960-1961). J-2-4

The use of explosives for the cutting of metals can be divided into several categories depending upon the dynamics of the cutting process. Three such major categories are (1) cutting with contact demolition charges, (2) cutting with linear shaped charges, and (3) cutting with explosively induced stress waves. All of these are of general value to the metals industry; however, each category is particularly suited for only certain types of cutting operations. Hence, the desired operation should be matched to the most appropriate technique. This paper presents the general considerations to be evaluated in the selection of a particular type of cutting charge.

Tardif, H. P., "Shaped Charge in Mining and Metallurgy", Canadian Mining Journal, 77 (7), 53-58, 75-76 (July, 1956). J-2-5

The article deals mainly with the use of shaped charges for mining and oil-well drilling.

Church, J. H., and Kessenich, G. J., "Apparatus for the Use of Shaped Explosive Charges", U. S. Patent No. 2,667,836 (February 2, 1954). J-2-6

The apparatus is for chambering and directing lined-shaped charges used for punching holes in metal. Also included in the invention is a system for initiating detonation of a lined-shaped charge.

Pearson, John, "Explosive Cutting, Welding, and Compacting of Metals", NOTS Technical Publication No. 2732, NAVWEPS Report No. 7760, In cooperation with ASTME (September 1, 1961); AD 264380. J-2-7

High explosives can be used to perform various metalworking operations, among which are metal cutting, welding, and the high density compaction of metal powders. Each of these three types of operations is discussed in terms of the dynamics of the process and the behavior of the material. Representative data are presented for each type of operation.

Cross References.

A-1-1-13 Describes damage to metal targets as a function of different metal linings of hollow charges.

A-1-1-27 Describes cutting action of Du Pont Flexible Linear Shaped Charge.

A-1-1-29 Discusses the techniques of using shaped charges and their applicability to specific metal-cutting problems.

A-1-1-33 Explains cutting with sheet explosive. The sheets can be cut to any size or shape.

F-1-0-41 Describes the use of explosives for expanding tubing and mentions possible techniques for metal cutting.

J-3-10 Discusses new explosive, EL-506, developed by Du Pont which can be shaped to any desired configuration.

## Metal Removal

### Shear Stress Cutting J-3

Davids, N., "Scabbing and Fracture of Materials by Stress Waves", Office of Ordnance Research, U. S. Army, OOR Project No. TB2-0001 (1253), Contract No. DA-36-016-ORD-465 (September, 1960). J-3-1

This report describes the results of a study of various related types of damage embracing cracking as a result of destructive interference by stress waves. Both linear behavior and more general stress-strain and failure criteria were assumed.

Drummond, W. E., "Comments on the Cutting of Metal Plates With High Explosive Charges", Journal of Applied Mechanics, 25 (2), 184-188 (June, 1958). J-3-2

The problem of cutting of metal plates with high-explosive charges is analyzed by treating the metal hydrodynamically. The hydrodynamic problem is solved in the linearized approximation and it is assumed that the metal splits wherever the pressure becomes sufficiently negative. It is shown that such negative pressures occur where two rarefaction waves meet and the predicted location of these splits is in qualitative agreement with experiment.

Evans, W. M., and Taylor, G. I., "Deformation and Fractures Produced by Intense Stress Pulses in Steel", Research, 5, 502-509 (November, 1952). J-3-3

The mechanism of plastic deformation and fracture due to high explosives is investigated by studying the fractures produced. Specimens are sectioned and etched. Metallographic photomicrographs are made to study the change in crystalline structure. The article presents illustrations of typical fractures.

Hall, C. M., and Royer, T. W., "Explosive Bolts", ASTME Report No. SP 60-165, Presented at Creative Manufacturing Seminars (1960-1961). J-3-4

This paper is a brief presentation of the current state of the art for potential users of explosive bolts and associated devices. It reviews typical applications and explosive component designs which have been successfully used. Since most users are concerned primarily with the mechanical characteristics of these devices, the paper is confined to those features. The pyrotechnics and explosive ordnance components used

in conjunction with the explosive bolts represent another field of technology equally broad in scope.

Kumar, S., and Davids, N., "Multiple Scabbing in Materials", Interim Technical Report No. 4, OOR Project TB2-0001 (1253), Pennsylvania State University for USA on Contract No. DA-36-061-ORD-465. J-3-5

This report discusses first, scabbing and multiple scabbing from a phenomenological point of view, then past experiments on scabbing with critical comments. It then suggests new types of experiments and the use of an inverse approach which could yield information on pulse shapes and some of the dynamic properties of the material. The relationships among these quantities have been determined graphically.

Kumar, Sudhir, and Davids, Norman, "Multiple Scabbing in Materials", Franklin Institute Journal, 263 (1573-1578), 295-302 (January-June, 1957). J-3-6

This paper discusses scabbing and multiple scabbing from a phenomenological point of view, and past experiments on scabbing with critical comments. It then suggests new types of experiments and the use of an inverse approach which could yield information on pulse shapes and some of the dynamic properties of the material. The relationships among these quantities have been determined graphically.

Kumar, S., "Scabbing in Bars and Plates - Further Studies", Interim Technical Report No. 13, OOR Project TB2-0001 (1253), Pennsylvania State University for USA on Contract No. DA-36-061-ORD-465. J-3-7

Scabbing, a fracture phenomenon in materials due to stress reversal of strong dynamic loads, is first discussed here from a phenomenological point of view. Then an elastic analysis for determining scab lengths both in bars and plates under plane stress and plane strain is presented. As a further refinement, after explaining briefly and applying the basic theory of elastoplastic wave propagation in solids, a study is made of scabbing possibilities in bars by semi-graphical methods, and also the basis for the elastoplastic analysis of scabbing in plates. Implications of both the elastic and elastoplastic analyses are compared. Idealized stress-strain relations for 14ST-4 Aluminum, obtained in our laboratory, have been used.

Kuman, S., and Davids, N., "Elastic-Plastic Analysis of Scabbing of Materials", Journal of the Franklin Institute, 265 (5), 371-383 (May, 1958). J-3-8

The graphical method is used to analyze stress propagation. Stress states are analyzed which can cause scabbing.

Kumar, S., "Some Further Studies on Scabbing in Materials", Proceedings Fifth Congress Theoretical and Applied Mechanics, Roorkee, India, Indian Society Theoretical and Applied Mechanics, Indian Institute of Technology, Kharagpur, India (1959). J-3-9

This paper presents a contour method for the analysis of scabbing which compares favorably with two methods previously introduced by the author, namely, the intercept and the stress-jump methods. Both bars and plates are considered in the analysis. The experimental results are compared with theoretical predictions with satisfactory agreement.

"Do It Yourself; Explosive Cutting", Steel, 144 (12), 104-105 (March 23, 1959). J-3-10

The use of a new explosive developed by Du Pont designated EL-506 is discussed as to its application for the cutting of metal parts. It has been used to cut metals up to one inch thick. The explosive is applied in direct contact with the metal surface by an adhesive and can be shaped to any desired configuration. The explosive work may be carried out with air or water stemming. The edges of the resulting cut are slightly ragged but technique is quick, easy, and reasonably safe.

"Explosive Forces Widen Metallurgical Studies", Steel, 127, 98-99 (November 20, 1950). J-3-11

This article describes experiments wherein mild-steel rod and tubing were coated with a thin layer of explosive. The rods burst from inside out, and a tube is formed. This is caused by shock waves meeting in the center along the axis of the rod. The metal in this region of high stress probably behaves as a liquid and exerts a high hydrostatic pressure on its surroundings. When the external pressure ceases, the piece flies apart violently. The same reaction occurs with tubing.

Nahmani, G., and Davids, N., "Scabbing of Steel by Plane Stress Waves", International Journal of Mechanical Sciences, 4, 73-81 (January, February, 1962). J-3-12

The lack of planarity of stress waves has hampered investigation of scabbing in the past. An arrangement is developed which produces plane detonation waves and is used for studying scabbing in metal-cylindrical plugs and plates. The results show that thickness of scabs is found to be greater than that expected from elastic-reflection theory alone, but proportional to explosive thickness and to the ratio of peak pressure to slope of the wave profile.

Temple, R., Jr., "Apparatus for Performing Work on Metal", Patent No. 2,323,758 (July 6, 1943). J-3-13

An explosively-powered tool is used to flatten and, if desired, simultaneously punch a hole in the metal being worked.

Parrish, N. C., "Explosively Released Nut", Patent No. 2,871,750 (February 3, 1959). J-3-14

The device is a machine nut which has a hollow chamber in it. This chamber is filled with explosive, so that when it is detonated, the nut shatters thus freeing the bolt.

Cross References.

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| A-1-1-33 | Explains the use of sheet explosives for shear-stress cutting. |
| F-1-0-6 | Discusses use of explosives to cut metal plates. |
| F-1-0-98 | Discusses cutting and punching operations with explosives. |
| F-1-4-3 | Describes cutting with the shock waves from an explosive charge. |
| J-2-1 | Investigates new methods of high-energy cutting including shear stress cutting. |
| J-2-4 | Describes cutting with explosively induced stress waves. |
| K-1-61 | Discusses propagation of Griffith-type cracks. |

## Material Behavior

Barber, Edda, and Sweitzer, Dorothy I., "Micrometeorites, High Velocity Impact Studies, and Problems of Space Travel Relating to Particle Impact", Jet Propulsion Laboratory, California Institute of Technology, for NASA on Contract No. NASw-6 (October 15, 1959). K-0-1

A bibliography of the work which has been conducted on high-speed impacting of materials is presented.

Barnes, C., "Study of Collisions, I. A Survey of the Periodical Literature", American Journal of Physics, 26 (1), 5-8 (1958). K-0-2

A review of the periodical literature on the subject of impact and the coefficient of restitution shows that the latter depends not only on the materials (elastic moduli) of the colliding objects, but also on (1) their relative normal velocity at the instant of impact, (2) their shapes and sizes, (3) their masses, and (4) the medium in which the impact occurs.

Barnes, G., "Study of Collisions, II. Survey of the Textbooks", American Journal of Physics, 26 (1), 9-12 (January, 1958). K-0-3

A survey of physical and engineering textbooks and periodicals indicates that there is a lack of agreement on the subject of impact and the coefficient of restitution. The

confusion arises primarily because of (1) the way in which the coefficient of restitution is so often defined, (2) the nature of the usual discussions of it, and (3) the reason given for its being less than unity for most collisions between objects of ordinary size. Ways of eliminating the difficulty are discussed.

Cook, Melvin A., "Mechanism of Cratering in Ultra-High Velocity Impact", Report AFOSR TN-57-486, Institute for the Study of Rate Processes, University of Utah, Salt Lake City, for USAF on Contract No. AF 18(603)-100 (July 10, 1957). K-0-4

The hydrodynamic theory of penetration of targets by shaped-charge jets is summarized and extended to account for crater volumes produced by shaped-charge jets. It is then applied in discussing cratering by single-particle projectiles in high velocity and in ultra-high-velocity impact, and cratering by multi-particle streams of independently penetrating particles. The conditions for impact explosions of targets and/or projectiles are discussed and theoretical results presented. Finally impact and explosion cratering are compared.

Cotner, J. R., and Weertman, J., "Bibliography on High Speed Deformation of Materials (1950-1961)", Northwestern University, Evanston, Illinois, to USAF on Contract No. AF 29(601)-4343 (May 15, 1961); AD 261376. K-0-5

Abstracts of the literature, from 1950-1961, dealing with high-speed deformation of materials are given in this bibliography. References concerning stress-wave propagation are included to aid in the understanding of the deformation. The arrangement of the abstracts is chronological with an alphabetic sequence within each year. An author index is included.

Culp, F. L., "Volume-Energy Relation for Crater Formed by High Velocity Projectiles", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-6

This paper combined with the one by Kineke from the same symposium shows that crater volume does not vary directly with energy or momentum. Evidence is shown to support the contention that it is quite impossible to infer the energy responsible for a given crater from a geometrical examination of the crater alone.

Davids, N., "Transient Analysis of Stress-Wave Penetration in Plates", Journal of Applied Mechanics, 26 (Series E), 651 (December, 1959). K-0-7

An analysis of the propagation of a transient-stress pulse concentrated at a point on the boundary of a plate whose thickness is of the order of a wavelength is presented. It is based on an expansion used by Caignard in geophysical-layer problems. Inside the plate it is found that there is a compressed zone which is relieved by a negative front traveling with the distortional wave velocity. When this interferes with a certain reflected negative front, the stress reverses in sign.

Davies, R. M., "The Determination of Static and Dynamic Yield Stresses Using a Steel Ball", Proceedings of Royal Society of London, 197 (A1050), 416-432 (1949). K-0-8

The static- and dynamic-yield stress of the material of a thick steel plate may be estimated by pressing and by dropping a hard steel ball on a plane surface of the plate which has been ground and then polished. Under these conditions, the first appearance of an indentation on the polished surface can be detected with good accuracy, either by an optical-interference method, or by an optical-reflection method. The static and dynamic experiments consist in finding the least force which must be applied to the steel ball to produce a permanent indentation. Using either the Guest-Mohr principal-stress difference or the von Mises shear-strain-energy hypothesis as criteria of failure, combined with an analysis of the stresses in the plate, it is shown how the appropriate yield stress can be calculated from the experimental data.

DeJuhasz, Kalman J., "Graphical Analysis of Impact of Bars Stressed Above the Elastic Range", Journal of the Franklin Institute, 248 (1), 15-48 (July, 1949). K-0-9

A number of impact problems of engineering interest are analyzed by means of a graphical method previously developed by the author. Problems considered comprise: impact at constant velocity of finite duration applied to one end of a bar, the length of the bar being infinite; bars of finite length, the other end being free, and the other end being fixed or restrained; impact stresses below yield stress (elastic range), and impact stresses above yield stress (plastic range). The history and gradient of stress and of velocity are represented in three-dimensional diagrams. The energy expended in impact, and its distribution into energy of plastic deformation, and into residual kinetic and elastic stress energy are determined. The total residual permanent strain is determined. The general treatment is supplemented with numerical examples.

Fastov, N. S., "Thermodynamics of Plastic Deformation", Doklady Akademii Nauk SSSR, 78 (2), 251-254 (May 11, 1951). In Russian. K-0-10

Derivation of an expression for free energy of a body undergoing plastic deformation with a given end velocity is given. Expressions for the relation between yield point, maximum elastic deformation, and rate of deformation, and between stress and deformation and its rate during plastic deformation and the shape of the stress-strain curve are presented. All agree qualitatively with experimental data.

Gehring, J. W., Jr., "An Analysis of Microparticle Cratering in a Variety of Target Materials", Proceedings Third Symposium Hypervelocity Impact, Chicago, October 7-9, 1958, Vol 1 (February, 1959). K-0-11

Experimental results of microparticle cratering are given. Particles of less than 200 microns traveling at velocities in excess of 10 km. per sec. have been used. The experiment needs to be refined in such areas as measuring penetration-diameter ratios.

Graham, Robert, "Impact Physics Bibliography", SCR-59, Sandia Corporation (December, 1958). K-0-12

Goldsmith, Werner, <u>The Theory and Physical Behavior of Colliding Solids</u>, Deward Arnold, Ltd., London (1960). K-0-13

The various chapters deal with the general case of impact of two bodies with three-dimensional motion wave transmission in elastic solids, longitudinal impact of a rigid mass on a rod, impact of visco-elastic bodies, and dynamic processes involving plastic strains.

Goranson, R. W., Bancroft, D., Burton, B. L., Blechar, T., Houston, E. E., Gittings, E. F., and Landeen, S. A., "Dynamic Determination of the Compressibility of Metals", Journal of Applied Physics, <u>26</u> (12), 1472-1479 (December, 1955). K-0-14

Equation-of-state data for Duralumin in the pressure range from 0.1 to 0.3 megabar have been determined dynamically by measuring shock and free-surface velocity electrically in a plate of 24ST Duralumin that has been stressed by a high-explosive detonation. A theory is presented which allows comparison with data obtained by other experimenters, and which yields the relationship between pressure and compression either at constant entropy or constant temperature. The empirical form chosen for the equation of state expresses the pressure as a quadratic function of the compression. Experimental techniques are described in detail. Five points are given for the equation of state of Duralumin in the pressure range from approximately 0.15 megabar to 0.33 megabar. Some data are also presented for cadmium and steel.

Gusein-Zade, M. I., "On the Acoustic Theory of Spalling", Applied Mathematics and Mechanics (Prikladnaia Matematika i Mekhanika), <u>24</u> (4), 547-49 (1958). In Russian. K-0-15

The paper deals with scabbing. A solution for an arbitrary force is represented in terms due to an impulse as a convolution integral. It is shown that face-spalling cannot occur, and for rear-spalling an expression for the depth where the destructive stress is attained is obtained. The solution differs from the one obtained by considering the point-force as a limiting case.

Hart, E. W., "A Uniaxial Strain Model for a Luder's Band", Acta Metallurgica, <u>3</u> (2), 146-149 (March, 1955). K-0-16

A relatively simple description of those properties of the band which may be termed classical is presented. It is shown that the mechanism which is responsible for the propagation of the band and which determines its velocity is independent of the classical plastic properties. A model is proposed to explain the load-elongation test behavior for materials which exhibit yield point phenomena.

Heller, S. R., Jr., "Structural Similitude for Impact Phenomena", David Taylor Model Basin Report 1071 (April, 1958). K-0-17

The conditions for geometric and dynamic similitude of structural models subjected to impact are developed. Various factors considered to have secondary influence on dynamic similitude are discussed, and their scale effects are explored.

Hodge, P. G., Jr., "Approximate Yield Conditions in Dynamic Plasticity", Proceedings of the Third Conference on Solid Mechanics, University of Michigan, April 1-2, 1957, The University of Michigan Press, Ann Arbor (1957). K-0-18

When an approximate yield condition is used to determine the static collapse load of a rigid-plastic structure, bounds of the error introduced are furnished by the theorems of limit analysis. However, for the case of dynamic loading no such general results are available. This paper considers such an approximation for the particular problem of a simply supported circular cylindrical shell subjected to a uniform pressure pulse. It is found that the errors are somewhat greater than in the case of static loading but that reasonable results are obtained if the two yield conditions are adjusted so as to predict the same static-collapse load.

Hodge, P. G., Jr., "Ultimate Dynamic Load of a Circular Cylindrical Shell", Proceedings Second Midwest Conference Solid Mechanics, Purdue University, September 8-9, 1955, Edwards Brothers, Inc., Ann Arbor (1955). K-0-19

A technique is presented for determining the deformation of a circular cylindrical shell due to an arbitrary dynamic loading. If a conventional requirement for the maximum deformation permissible in the shell is adopted, the ultimate dynamic load of the shell is obtained. Finally, this ultimate load is expressed in terms of the distance of the shell from the point of origin of the dynamic pressure pulse.

The basic theory necessary to calculate the static collapse load and the dynamic effects of loads in excess of this value is presented. This theory is based upon a rigid-plastic material and a simplified yield condition. The pressure pulse due to the blast may have an arbitrary shape. The results are applied to several examples. Some objections to the theory and some suggestions for overcoming them are discussed in detail.

Huth, J. H., Thompson, J. S., and van Valkenburg, M. E., "Some New Data on High-Speed Impact Phenomena", Paper 56-A-15, Presented at the ASME National Meeting, New York (November, 1956). K-0-20

A summary of recent experiments aimed at determining the role of physical parameters in high-speed impact phenomena is given. An equation is derived for the penetration into thick targets by projectiles of the same material.

Huth, J. H., and Cole, J. D., "A Theoretical Treatment of Spalling", Project RAND Research Memorandum RM-1181, Rand Corporation (January 27, 1954); AD 109957. K-0-21

A method for the prediction of spall thickness and diameter is given and has been applied successfully in checking experimentally produced spalls in both steel and glass. This tends to confirm the belief that spalling can be described elastically and is produced by the reflection of a one-dimensional head rather than by a nonuniform spherical wave as has heretofore been assumed.

Hudson, G. E., "A Theory of the Dynamic Plastic Deformation of a Thin Diaphragm", Journal of Applied Physics, 22 (1), 1-11 (January, 1951). K-0-22

The theory presented in this article was developed in an attempt to describe the observed motion and plastic deformation of clamped metal diaphragms used in certain underwater explosion experiments and in certain mechanical gauges. The theoretical attack on this problem enables one to set up certain equations of motion, which may be solved in finite form under certain conditions. The solutions enable one to specify, for instance, the final deformed diaphragm profile, the distribution of thickness after deformation, the swing-time, which is the total time for deformation to take place, and many other quantities.

The simplest case, termed the "elementary approximation", turns out, except for relatively minor details, to describe adequately for many purposes the motion and final shape of the diaphragm; it is found that the deformed diaphragm shape is conical, the thickness distribution shows a marked dimpling at the center of the diaphragm, and the swing-time $t_s$ is, to this order of approximation

$$t_s = a/c,$$

where a is the radius of the diaphragm, and c is the square root of the ratio of the "yield stress" to the density. These results are all in good agreement with experimental facts.

James, H. J., and Buchanan, J. S., "Experimental Studies of Penetration by Shaped Charge Jets", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-23

It is shown that instantaneous values of penetration velocity are not always constant with theory; for the jets with velocities of 7800 to 4500 meters per second, penetration and velocities produced agree with theory; the data does not agree with theory below 4500 meters per second. No relation is evident between depth of penetration and strength of target. There are relationships between the strength of the target and both the volume and the diameter of the crater formed.

Kineke, J. H., Jr., "An Experimental Study of Crater Formation in Lead", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-24

Part of an investigation described by Gehring in the same symposium is presented. Most of the attention has been on steel pellets impacting lead. An attempt was made to discern a transition in cratering mechanism which might occur when impact velocity was greater than plastic wave velocity. The ratios of crater depth to diameter, and crater volume to impact energy were measured.

Koehler, J. S., "On the Dislocation Theory of Plastic Deformation", Physical Review, 60 (Second Series), 397-410 (September 1, 1941). K-0-25

A detailed study has been made of the lattice imperfections which are assumed to account for plastic deformation. Calculations of the strain energy associated with these dislocations have been made in the following cases: a dislocation in a uniform shear stress, two dislocations in an infinite medium, and a dislocation near a surface. The force acting on a dislocation is found by taking the gradient of the strain energy. A force is found which tends to attract dislocations toward the surface of a specimen. It is shown that about twice as much energy is required to produce a certain amount of slip inside a solid as is required to produce the same amount of slip at the surface. The energy required to produce a dislocation is found to be several electron volts per atomic plane, the exact amount depending on where it is located and how it was produced. Finally the energy stored in a material during work hardening is calculated by assuming that the dislocations are arranged in a regular two-dimensional lattice in the material. The density of dislocations found for severely work-hardened material agrees with the predictions of other investigators. Numerical values found for the energy stored during work hardening are in agreement with experiment.

Kilsky, H., and Shearman, A. C., "Investigation of Fractures Produced by Transient Stress Waves", Research, 2 (1), 384-389 (1949). K-0-26

The mechanism of fracture due to detonation of explosives is studied by observing the fractures of bodies of various shapes. Plastic bodies are used. Large plates, small plates, cylinders, and cones are investigated. Various fractures are well illustrated.

Kymer, J. R., "Experimental Studies in Armour-Penetration", International Symposium Stress Wave Propagation Materials, Interscience Publishers, Inc., New York (1960). K-0-27

A review of armour penetration effects, a review of experimental techniques used to study the mechanisms of armour penetration and a discussion of types of armour and projectile failure are given. Some of the parameters such as geometry and mass of projectile, thickness of plate, angle of attack, and mechanical properties of materials and their effects on penetration are also discussed.

Lee, E. H., and Tupper, S. J., "Analysis of Plastic Deformation in a Steel Cylinder Striking a Rigid Target", Journal of Applied Mechanics, Transactions ASME, 21 (1), 63-70 (March, 1954). K-0-28

The G. I. Taylor dynamic-compression test is used to determine the entire strain distribution for a test cylinder of nickel-chrome steel. In the interpretation of results, interest is concentrated on the plastic- and elastic-wave fronts which emanate from the surface of contact. The theory of the propagation of plastic waves is presented. This is a fundamental article in relation to impacts (velocities to about 1500 fps) large enough to cause plastic deformation.

Mann, H. C., "High-Velocity Tension-Impact Tests", American Society for Testing Materials Proceedings, 26 (Part 2), 85-109 (1936). K-0-29

Data are presented which definitely show that high-velocity tests are essential to reveal the true dynamic properties of materials. The results obtained further indicate that in the selection of materials for use under conditions involving dynamic loading the following three significant factors must be considered:

1. The transition velocity within which normal material behavior may be expected.
2. The ratio of total-energy value to mass or volume of material involved.
3. The effect of surface irregularities such as tool marks, size and form of fillets, etc.

The high-velocity tension-impact machine designed and built for this investigation is described, and the mathematical derivation of the equation used to calculate the energy required for rupture is given.

Diagrams and photographs of typical fracture transitions are presented, showing the effect of velocity on both ferrous and non-ferrous materials.

Mannix, W. C., Atkins, W. W., and Clark, R. E., "Proceedings of the Second Hyper-Velocity and Impact Effects Symposium", Vol 1, May 22-24, 1957, U. S. Naval Research Laboratory, Washington, D. C. (December, 1957); AD 201902. K-0-30

The papers presented at this symposium are titled: "The Acceleration of Small Particles With High Explosives"; "Acceleration of Masses to Hypervelocities by Explosive Means"; "Thermodynamic Properties of Gases at High Temperatures: Properties of Air and Its Constituents to One Million Degrees"; "The NMSM-NOTS Light-Gas Gun"; "Meteor Distribution and Cratering"; "Problems in Meteoric Erosion"; "Basic Consideration in the Development of High Speed Hypersonic Wind Tunnels"; "Cratering by a Train of Hypervelocity Fragments"; "High-Velocity Impact Studies at the University of Utah"; "Magnetoaerodynamics"; "Progress Report on Axisymmetric Wave Fields"; "Velocity Terms and Units"; "Study of Electromagnetic Gun"; "A 4-Coil Induction Accelerator"; "The Coil Type of Electromagnetic Accelerator"; "Acceleration of Masses to Hypervelocities by Electromagnetic Means"; "Mechanical Effects of Asymmetric Magnetic Fields"; and "The Acceleration of Exploding Wire Plasmas by Asymmetric Magnetic Fields".

McDonough, J. P., and Hegge, E. N., "Observations of Projectile Impacts of Sand Particles at Velocities Ranging from 2900 ft. per sec. to 7000 ft. per sec.", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-31

Information on the effects of rain and dust erosion and meteoric impact on high-velocity aircraft and missiles is presented. Results for aluminum projectiles impacting freely-falling sand particles are discussed.

McKenzie, R. J., Martin, F. F., and Kentworthy, H. M., "High Velocity Impact of Small Metal Spheres Upon Flat Metal Targets", Proceedings Third Symposium Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-32

This paper presents and discusses some of the data, analyses, and observations associated with two series of fragment-target impacts. Several expressions relating penetration and cratering with velocity and other parameters correlated to those data are introduced. Plates were impacted by spheres of unlike metal.

Morrow, C. T., "Shock Spectrum as a Criterion of Severity of Shock Impulses", Journal of the Acoustical Society of America, 29 (1), 596-602 (1957). K-0-33

Shock impulses have not as yet yielded to any practical method of spectral analysis that would permit convenient exact calculation of all the peak internal responses of hardware subject to such accelerations, and also permit comparison of shock severities by inspection. The shock spectrum with a few supplementary techniques provides adequate insight into the responses of a one degree of freedom resonator. As an indication of the responses of a system with several coupled degrees of freedom, a second-order shock spectrum is defined. An oscillatory constituent of the spectrum is also defined in such a way as to be applicable to any order of spectrum. Investigation of these two concepts leads to the conclusion that if the first-order shock spectrum technique is to be used as a basis for comparison of the severity of a laboratory test shock with that of a service shock, spectra should be plotted for both positive and negative directions. Moreover, when feasible, such spectra should ordinarily be plotted as distinct curves for the intervals during and after the test shock, and the oscillatory constituent for the interval during the shock should be estimated.

Mott, N. F., "Fragmentation of Shell Cases", Proceedings of the Royal Society of London, 189 (1018), 300-308 (1947). K-0-34

A theory is given of the breakup of the metal case of a cylindrical ring bomb, in which the lines of fracture perpendicular to the axis of the bomb are predetermined. From the theory an expression is given for the length of the average fragment; this is shown to depend, if certain hypotheses are made, on the radius and velocity of the case at the moment of breakup and on the mechanical properties of the metal.

Murray, W. M., "Effects of Shock Loading", Product Engineering, 25 (12), 171 (1954). K-0-35

A shock load was found to be not always equal to twice the static load of the same numerical magnitude. Whether or not there will be any dynamic effects as well as the magnitude of these effects will be determined by the ratio of the time rate of application and duration of the load to the natural period of the structure.

O'Brien, J. L., and Davis, R. S., "On the Fracture of Solids Under Impulsive Loading Conditions", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), 371-388. K-0-36

The well-known scabbing or spalling phenomenon that is associated with the reflection of a compression-stress wave from a free surface is discussed, both in terms

of the previous work in this field and the recent results obtained by the authors. In addition, multiple pellet technique for obtaining the pressure profile of an incident compression shock is discussed. The reported dependence of stress for fracture as a function of the intensity of the incident compression at the position of fracture is explained in terms of errors introduced by the techniques used to measure shock profiles.

Owens, R. H., and Symonds, P. S., "Plastic Deformation of a Free Ring Under Concentrated Dynamic Loading", Journal of Applied Mechanics, ASME Transactions, 77, 523-529 (December, 1955). K-0-37

The deformations of the ring are determined for the points at which the force is such that the plastic deformations are large compared with the elastic strains. It is shown from energy considerations how the results for a rectangular force pulse may be used to obtain fair estimates of the deformations from a force pulse of quite different shapes.

Partridge, W. S., Vanfleet, H. B., and Whited, C. R., "Crater Formation in Metallic Targets", Journal of Applied Physics, 29 (9), 1332 (September, 1958). K-0-38

Spheres impacted large targets of the same material and the craters produced were measured. The volume of the crater produced was directly proportional to the kinetic energy of the sphere. The penetration varied linearly with the velocity of momentum of the pellet. The area of the crater as measured in the plane of the original surface of the target was directly proportional to the momentum of the sphere.

Partridge, W. S., Morris, C. R., and Fullmer, M. D., "Perforation and Penetration Effects of Thin Targets", Proceedings of the Third Symposium on Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-39

The impacting of glass and aluminum with steel and tungsten spheres of known mass is discussed. Energy lost during perforation and energy necessary to just perforate the targets were determined. For glass, more radical cracks, shattering, and powdering are observed at the higher-impact velocities.

Partridge, W. S., and Clay, W. G., "Studies of High-Velocity Impact in Wax", Journal of Applied Physics, 29 (6), 939-942 (June, 1958). K-0-40

Penetration of wax pellets into wax targets was found to vary linearly with the cube root of the pellet mass and the pellet velocity up to velocities in excess of twice the sonic velocity in the wax target. The crater area varies directly as the impact velocity, but there is a marked increase in the constant of proportionality above the target sonic velocity. The volume of the crater per unit energy of the pellet was found to be $2.23 \times 10^{-8}$ $m^3/j$ for the lower velocity range and above the target sonic velocity the value was found to be $2.75 \times 10^{-8}$ $m^3/j$. It was observed that a large part of the crater volume is created by deformation of the target material and that only a small part is due to ejection of the target material.

Pearson, John, and Rinehart, John S., "Deformation and Fracturing of Thick-Walled Steel Cylinders", Journal of Applied Physics, 23 (4), 434-441 (April, 1932). K-0-41

Tests have been conducted on annealed heavy-walled cylinders of low-carbon (1020) steel internally loaded by explosive charges. The purpose of these tests was to obtain basic information on the manner and type of fracturing and plastic flow obtained by extremely high pressures acting for short durations. It was observed that all of the cylinders tended to fracture in long fragments in the same basic pattern, but with variations because of wall thickness and manner of loading. Experimental results indicate that the radial-cleavage type of fracture is initiated within the cylinder wall and propagated to the surface, while the shear-type fracture associated with the inner portion of the cylinder wall appears as an independent-energy relieving process.

Microstructure analysis of the cylinder fragments shows a definite relationship between the type of fracture and the amount of distortion of the grain boundary. Considerable shock twinning is present in the cylinder fragments, and the grain structure near the inner surface shows severe distortion and flow. Strain measurements indicate that considerable plastic strain occurs during the explosive loading and cleavage fractures were always observed to occur in association with considerable plastic deformation.

Pearson, John, "Some Material Behavior Patterns in Explosive Working", ASTME Report No. SP 62-07 presented at Creative Manufacturing Seminars (1961-1962). K-0-42

The outline of a program at China Lake Naval Ordnance Test Station to investigate basic material characteristics under explosive loading is presented. A discussion of the wide range of material behavior patterns which are possible in explosive metal working operations, areas where additional engineering data are needed, and a description of two diverse study programs are presented. Even with the wide variation of conditions which are presently being utilized in explosive forming operations it was concluded that the basic mechanisms for plastic flow and fracture seem to be the same in all operations.

Petersen, Alfred H., High Energy Rate Metal Forming, ASM Pamphlet. K-0-43

Metal behavior during explosive forming is explained by dislocation theory. Calculations indicate that explosives detonated in intimate contact with metal surfaces can create pressures beyond 300,000 atmospheres. There is evidence that under such pressures, metals behave as viscous fluids.

Pian, T. H. H., "Dynamic Response of Thin Shell Structure", Second Symposium on Naval Structural Mechanics (1960). K-0-44

A report is presented of work at the Massachusetts Institute of Technology on the dynamics of thin-shell structures in the plastic range. Two problems are discussed - the problem of large plastic deformation of shells under intensive loading of very short duration, and the problem of the dynamic response of thin shell beams after a buckling failure has occurred.

Pukl, S., "Dynamic Loads With Special Consideration of Impact", Parts I and II, Nase Gradevinarstvo Beograd, 10, 259, 505 (March, April, 1956). In Serbian. K-0-45

The physical phenomena at the point of application of kinetic energy, the impact mass, and time must be considered in dynamic loads. Two cases are mathematically presented: in the first, the whole kinetic energy from the loading is transformed into deformation or oscillations; in the second, only local deformation of failure at the point of application results.

Rice, M. H., McQueen, R. G., and Walsh, J. M., "Compression of Solids by Strong Shock Waves", Solid State Physics, Vol 6, Seitz and Turnbull Edition, Academy Press, Inc., New York (1958). K-0-46

This paper has four main parts: hydrodynamic relations; a review of experiments to determine the pressure-compression states behind shock waves; experimental data extended to a complete thermodynamic description of state neighboring the experimental curves; and the Dugdale-MacDonald relation tested at zero pressure.

Rinehart, John S., "The Behavior of Metal Under High and Rapidly Applied Stresses of Short Duration", NAVORD Report 1183, NOTS 239, U. S. Naval Ordnance Test Station, Inyokern, California (September 27, 1949). K-0-47

A number of interesting effects produced as the result of detonating explosive charges in intimate contact with metal plates, rods, and tubes are described. The principal observable effects are (1) fracturing of the metal caused by a tensile-stress produced as the result of the reflection of a high-compressional stress wave at a free boundary, (2) the fracturing of the metal caused by high-stress concentration, and (3) permanent straining of the metal.

Rinehart, J. S., "Some Observations on High Speed Impact", Popular Astronomy, 58, 458-464 (1950). K-0-48

This paper summarizes much of the experimental data that exist in phenomena associated with the impact of high-speed particles; specifically, it discusses the impact of 20,000 feet-per-second particles produced by shaped charges, and the mechanics and energetics of crater formation.

Rinehart, John S., "Some Quantitative Data Bearing on the Scabbing of Metals Under Explosive Attack", Journal of Applied Physics, 22 (5), 555 (May, 1951). K-0-49

Scabbing, sometimes called spalling, is the fracturing of a material near one of its free surfaces relatively far removed from the area of application of the pressure (or stress) impulse. Viewed qualitatively, the metal fractures because its strength is exceeded as a result of the reflection of the compressional-stress wave as a tension wave. Geometrical considerations indicate that if a plate scabs as a result of reflection of a

high-intensity transient compressional-stress wave at a free surface, the thickness of the scab should be governed principally by one of two factors – the shape of the stress wave or a critical normal fracture stress that is characteristic of the material acted upon. Formulation for the development of this theory and experimental results to support it are given.

The results of this testing indicated that the plastic-flow mechanism responsible for decay is relatively uneffected by an alloying agent, whereas the resistance to fracture may be greatly increased. Scabbing has been found to be governed principally by the spatial distribution of pressure within the wave and by a critical normal-fracture stress that is characteristic of the material under attack. There is some evidence that the latter is influenced by the state of stress existing in the material at the time the fracturing occurs.

Rinehart, John S., "Some Experimental Indications of the Stress Produced in a Body by an Exploding Charge", Journal of Applied Physics, 22 (9), 1178-1181 (September, 1951). K-0-50

Whenever an explosive charge is detonated on the surface of a body, a large amount of energy is introduced into the body in the form of a high-intensity compressional-stress wave of short duration. The energy in this wave distributes itself within this body and eventually becomes dissipated. The absorbed energy appears, at least in part, in the form of observable inelastic deformations. A careful examination of these deformations throws considerable light on the probable nature of the stress distribution that must have existed in the body after detonation of the charge. The effects produced by small cylindrical charges that were detonated on the surfaces of large annealed medium steel plates are described in this paper.

Rinehart, J. S., and Pearson, J., "Some Tensile Fractures Generated in Metals by Impulsive Compressional Loading", Paper presented at meeting of American Physical Society, Berkeley, California, December 27-29, 1951, Abstract in Physical Review, 85 (4), 768 (February 15, 1952). K-0-51

One aspect of the part that high-intensity stress waves play in the fracturing of metal cylinders subjected to internal explosive loading has been studied. It has been found that tensile type fractures will result from the interference of reflected tensile-stress waves whenever the resulting tensile stress exceeds the critical normal fracture stress of the material. Stress-wave velocities have been measured for low-carbon steel, brass, copper, lead, and aluminum alloys from the geometry of fracture. These velocities are in reasonable agreement with accepted values for the velocities of dilational waves in these metals.

Rinehart, J. S., and Pearson, J., "Fracturing Under Impulsive Loading", Report NOTS-TM-930, U. S. Naval Ordnance Test Station, Inyokern, California (August, 1952); ATI 204553. K-0-52

Problems peculiar to fracturing under impulsive loading are discussed. Many examples of fracture patterns that result from the high transient stresses generated by

explosive charges are described. Particular attention is paid to the conditions that lead to fracturing and to the very pronounced effects that the physical properties of the materials play in the fracturing process. It is demonstrated that fracturing under impulsive loading can, for the most part, be considered an orderly rather than a random process. Generally, the fracture patterns can be related to trajectories of maximum shear or surfaces over which the principal normal stress is a maximum. In almost every case, the transient inhomogeneities of stress that lead to fracturing can be established at least qualitatively.

Rinehart, J. S., "Scabbing of Metals Under Explosive Attack, Multiple Scabbing", Journal of Applied Physics, 23 (11), 1229-1233 (November, 1952). K-0-53

The mechanism of multiple scabbing is explained in terms of stress-propagation theory. Experimental results are shown which verify the theory. Particle velocities are determined by the use of pellets in a hole drilled on the back of the plate.

Rinehart, John S., and Pearson, John, "Conical Surfaces of Fracture Produced by Asymmetrical Impulsive Loading", Journal of Applied Physics, 23 (6), 685-687 (June, 1952). K-0-54

Conical surfaces of fracture generated in thick-walled cylinders that were asymmetrically and impulsively loaded through the use of internal explosive charges are presented. It is deduced from qualitative considerations that the conical fractures result from the interaction between transient tensile-stress waves. The two tensile-stress waves that are responsible for the fracture arise from a single compressional-stress wave that is reflected from two inclined free surfaces. The angle of fracture associated with these conical surfaces has been used to measure the velocity of propagation of the stress waves in low-carbon steel, brass, copper, lead, and 24ST aluminum alloy.

Rinehart, J. S., "Surface Energy, a Mode for Energy Absorption During Impact", American Journal of Physics, 21 (4), 305-307 (April, 1953). K-0-55

The role that pulverization of the target material may play in absorbing the energy of an impacting missile is discussed. The energy that can be absorbed in this way will, in general, depend on the area of new surface that is created. Approximate calculations suggest that for impacts against rock-like materials and glass very considerable amounts of energy could be absorbed; the production of rock flour at the Barringer Meteorite Crater in Arizona is cited as an example.

Rinehart, John S., and Pearson, John, Behavior of Metals Under Impulsive Loads, American Society for Metals, Cleveland (1954). K-0-56

This book discusses the character of impulsive loading, indicates the conditions under which such loading can develop, and describes the main phenomenon that becomes involved when materials, primarily metals, and systems of material bodies are subjected to rapidly applied loads of short duration.

Rinehart, John S., "Metals Under High Speed Loading", The Mines Magazine, 49 (2), 19-25 (February, 1959). K-0-57

This article is based on a lecture presented at the Pennsylvania State University Short Course in Mechanical Properties of Materials, July 10, 1958.

Rinehart, John S., "Fracturing Under Explosive Loading", Chemical Engineering Progress, 55 (2), 59-64 (February, 1959). K-0-58

The mechanics and physics of the fracturing of metals is discussed. The article covers work performed on the explosive coupling of metals for solids in the form of plate and bar as well as heavy walled cylinders with the explosive on the outside in one case and on the inside in other cases. The presence of tensile fractures occurring during the expansion phase and of shear fractures during the release phase of cylindrical solids explosively loaded is demonstrated.

Rossard, C., and Blain, P., "Initial Results of Research on the Hot Deformation of Steels; Application of a Specially Designed Apparatus", Revue de Metallurgie, 55 (6), 573 (June, 1958). In French. K-0-59

After a period of damped oscillations, the stress attains a constant value for a given speed of deformation and a given temperature. A law of variation of characteristic stress as a function of deformation and temperature is deduced.

Shapiro, G. S., "Longitudinal Oscillations of Bars", Prikladnaia Matematikh i Mekhanika, 10 (5), 597-615 (1946). In Russian. K-0-60

This paper deals with longitudinal oscillations of bars whose materials do not follow Hook's law, as well as non-elastic longitudinal oscillations. Discussions of nonlinear problems of longitudinal oscillation, propagation of one-directional waves, reflection of waves due to sudden changes in cross section of the bar and modulus of elasticity, and bars of variable cross section are presented. Hook's law is derived as a particular case and the author points out the error in the results of L. Donnell for the problem of reflection of waves and for the problem of oscillation of bars of variable cross section. These results are obtained by the method suggested by S. Christianvich for investigations of unsteady flows in open channels.

Shewmon, P., and Zackay, F. G., Editors, Response of Metals to High Velocity Deformation, Papers presented at Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, Inc., New York (1961). K-0-61

Sixteen papers of research work being conducted on the response of metals to high-velocity deformation are reported. The papers are of importance and have been listed separately under the subject category.

Shkenev, Yu. S., "Deformation of Free Cylindrical Shells Subject to Impulses", Inzhenernyy Sbornik Akad Nauk SSSR, 26, 54-58 (1958). In Russian. K-0-62

The author assumes that the shell is elastically isotropic and freely located in space and that the load impulse is uniformly distributed along the meridian line of the shell. Deformation is treated as two-dimensional and the Kirchhof theory of a curved slender beam is used. An arbitrary relation load and time was assumed.

Shreffler, R. G., and Deal, W. E., "Free Surface Properties of Explosive-Driven Metal Plates", Journal of Applied Physics, 24 (1), 44-48 (1953). K-0-63

A photographic technique for study of metal free surfaces under acceleration by high explosives is presented. Methods for reducing the data from the photographic record are described. Specific results using brass plates driven by explosives are cited.

Simmons, J. A., Jauser, F., and Dorn, J. E., "Mathematical Theories of Plastic Deformation Under Impulsive Loading", Series No. 133, Issue No. 1, Minerals Research Laboratory, University of California, Berkeley (December, 1959). K-0-64

This paper presents a unified formulation of the mathematical theory of wave propagation in solids subjected to impulsive loading. The two currently popular theories of plastic wave propagation, proposed by von Karman and Malvern, respectively, are treated as special cases of the more general treatment. A review of these specializations emphasizes those features of plastic deformation under impulsive loads that are uniquely different from those obtained under more slowly applied loads. It is shown that the various theories of plastic-wave propagation differ only with respect to the assumed mechanical behavior of materials. The theoretical deductions are compared with the experimental facts to illustrate the possible utility and limitations of the existing theories. It is shown that neither the von Karman nor the Malvern assumptions of the behavior of materials is completely realistic for impulsive loading of metals and proof is offered that it is not possible to extrapolate the known empirical behavior of crystalline materials under nominal rates of deformation to rates encountered under impulsive loading. Finally, it is shown that further progress in understanding the propagation of plastic waves in crystalline solids is dependent upon the formulation of the laws of motion of dislocations under impulsive-loading conditions.

Singh, Sampooran, "Spatial Distribution of Fragments of Explosively Loaded Thin-Walled Steel Cylinders", Physical Society of London Proceedings, 69 (Section 13), 1089-1094 (1956). K-0-65

This paper describes the spatial distribution of fragments on static detonation of a thin-walled steel cylinder internally loaded with explosives. The fragments on striking a mild steel 'witness-plate' produce a fragmentation pattern and a simple analysis of its geometry indicates the direction of emission of the fragments. Experimental results indicate that the direction of emission of most of the fragments make an angle of 7-5° to the normal to the inner surface of the cylinder and away from the exploder.

Summers, J. L., and Charters, A. C., "High-Speed Impact of Metal Projectiles in Targets of Various Materials", Proceedings of Third Symposium on Hypervelocity Impact, Chicago, Illinois, October 7-9, 1958, Vol 1 (February, 1959). K-0-66

Methods of determination of the damage caused by small bodies such as meteoroids impacting against the surface of a space vehicle are discussed. The projectiles were spheres or rods impacting at both normal and oblique angles with velocities from a few hundred feet per second to nearly 12,000 feet per second.

Summers, J. L., and Niehaus, W. R., "A Preliminary Investigation of the Penetration of Slender Metal Rods in Thick Metal Targets", NASA TN D-137, National Aeronautical Space Administration (December, 1959). K-0-67

The experimental results of firing steel and tungsten-carbide rods into copper, lead, and steel at velocities to about 11,000 feet per second are discussed. Rods impacting at velocities approaching fluid-impact region were compared with the jets of shaped-explosive charges. The rod-produced craters were much larger.

Swaiger, K., Analysis of Deformation, Vol 1, Chapman and Hall, Ltd., London (1953). K-0-68

Formulation of the mathematically-linear theory analyzing deformation is given. General inferences are drawn without solving equations and boundary conditions for particular cases.

Taylor, Sir Geoffrey Ingram, "The Testing of Materials at High Rates of Loading", Institution of Civil Engineers Journal, 26, 486-519 (1946). K-0-69

This paper describes some of the ways in which the strength properties of materials at high rates of strain can be deduced from results of dynamic experiments. The difficulties in the way of testing at high rates of straining are of quite a different order of magnitude from those at ordinary laboratory speeds. In some cases the effects of inertia may be separated from real changes due to speed of loading in the strength properties of the material. The case of plastics, where the material has a memory for its past strain-history, is more difficult to separate.

Thiruvenkalachar, V. R., "Recent Research in Stress in India", International Symposium Stress Wave Propagation Materials, Interscience Publishers, Inc., New York (1960). K-0-70

Consideration of experiments on explosively-loaded steel cylinders is given. Results of scabbing experiments in thin metallic plates are presented. A mathematical solution of stress propagation in an infinite slab initiated by an impulsive load over a finite area of one face of the slab is given.

Van Valkenburg, M. E., Clay, Wallace G., Huth, J. H., "Impact Phenomena at High Speeds", Journal of Applied Physics, 27 (10), 1123-1229 (October, 1956). K-0-71

A study of high-speed metal-to-metal impact in the velocity range 1 to 5 mm/$\mu$sec using 1/8-inch-diameter spherical pellets is described. Pellet materials include aluminum, magnesium, steel, brass, lead, and zinc. Experiments relating to the mechanisms of cratering and the perforation of thin targets are presented. For the 1/8-inch-diameter spherical pellets, it is found that the volume of the crater per unit energy of the impacting pellet is essentially constant for each material and that the penetration is proportional to the velocity of the pellet so long as the pellet velocity is less than the velocity of sound in the target material. An attempt to model very high-speed impact by using soft wax targets in which the sonic velocity is less than the impacting velocity is outlined.

Valorinta, V., "Influence of Temperature and Speed of Deformation on the Deformation Resistance of Some Steels", Werkstattstechnik und Maschinenbau, 48, 452 (August, 1958). In German. K-0-72

Deformation resistance decreases as temperature increases and increases as deformation speed increases. In the first case, a transitory sudden increase of deformation resistance was observed within the temperature range of recrystallization; the more accentuated, the lower the deformation speed.

Vanfleet, H. B., Partridge, W. S., and Cannon, E. T., "The Anomalous Behavior of Lead-to-Lead Impact", Proceedings of Third Symposium on Hypervelocity Impact, Chicago, Illinois, October 7-9, Vol 1 (February, 1959). K-0-73

In obtaining data on the effect of the size of the impacting spheres on the physical dimensions of the craters, a series of lead spheres of three diameters were accelerated into thick lead targets. Data for each shot were the volume, diameter, and depth of the crater, and the velocity of the sphere. For 1/8-inch spheres at high energies there is not a linear relationship between energy and the volume of the crater.

Rinehart, J. S., Philipchuck, V., and Pearson, J., "Some Aspects of Explosive Forming Techniques", The Engineers' Digest, 20 (4), 154-155 (April, 1959). K-0-74

This article is a three-way discussion about what happens to metal when it is subjected to the high strain rates generated by explosive force. Metal passes through an elastic and plastic state of stress but never becomes fluid. The individual bonds between the atoms are subjected to several, often opposing, stresses because of the nature of the external force.

Walsh, J. M., Shreffler, R. G., Willig, F. J., "Limiting Conditions for Jet Formation in High Velocity Collisions", Journal of Applied Physics, 24 (3), 349-359 (March, 1953). K-0-75

The high-velocity collision of two solids is discussed as a problem in compressible-fluid hydrodynamics. Such collisions may conveniently be divided into jetless and jet-forming categories. A theory is presented which describes flow in the collision region for the jetless case and determines a critical collision angle (as a function of material velocities and equation-of-state properties of the materials) above which a jet must arise from the collision. The experimental study of solid collisions utilizes metal plates driven by high explosives, the impact of the plates being recorded with a high-speed smear camera. Two experimental arrangements are used, and data for collisions employing Dural, mild steel, brass and lead are presented. Jetless and jet-forming collisions are observed, and critical angles separating the two types are compared with theoretical predictions. Agreement seems sufficiently good to indicate that the theory is valid.

White, Merit P., "The Force Produced by Impact of a Cylindrical Body", Armor and Ordnance Report No. A-157, National Defense Research Committee (March 8, 1943); ATI 25207. K-0-76

A method for calculating the value of the maximum impact force produced by the compressive impact of a cylinder of ductile material against an unyielding surface is given. Two kinds of behavior are possible in compression of impact: (1) the material of the moving specimen is brought to rest by the agency of the stress waves propagated from the impact zone, as in low-velocity impact; or (2) the material is not stopped, but flows radially from the impact zone parallel to the critical velocity, whereupon a sudden decrease occurs. Beyond this value the impact force increases continuously, and for very large velocities approaches the force produced by a fluid stream of the same density, velocity, and area.

Zaid, M., and Paul, B., "Mechanics of High Speed Projectile Perforation", Journal of Franklin Institute, 264 (2), 117 (August, 1957). K-0-77

Perforation of thin plates by high-speed projectiles is considered from a momentum viewpoint. Equations representing the magnitude and direction of forces, velocity, etc., as a function of penetration distance are derived for the conical projectile under normal impact. Good correlation between theory and experiment is obtained.

"The Basic Theory of Scabbing in Materials With Two Solids in Contact, Part I, Elastic Theory", Interim Technical Report No. 1, Pennsylvania State University, to USA on Contract No. DA-36-061-ORD-465. K-0-78

Basic relationships for scab formation in a solid are developed from the point of view of elastic materials. Relationships giving the thickness of scabs are obtained for semi-infinite plates and thin rods on the basis of normally-incident pressure pulses for arbitrary form. The effect of a backing medium has been expressed in terms of impedance matching relations between the two media, and these were used to determine quantitatively the reduction in stress. Criteria for required thicknesses are developed on the basis of momentum considerations. A preliminary treatment is included for spherically-diverging waves arising from a point explosion in a semi-infinite medium.

Some available data are made use of in a discussion for the purpose of evaluation time constants of typical pressure pulses used in the report.

"Proceedings of Third Symposium on Hypervelocity Impact (October 7-9, 1958)", Vol 1, Armour Research Foundation of Illinois Institute of Technology, Chicago, for U. S. Army, U. S. Navy, and U. S. Air Force on Contract No. DA 11-022-509-ORD-2721 (February, 1959). K-0-79

The individual papers presented at this symposium are abstracted in appropriate sections of this bibliography.

Rinehart, J. S., Philipchuck, V., and Pearson, J., "Why Explosive Forming Works", Steel, 144 (3), 62-65 (January 19, 1959). K-0-80

This article is composed of three separate papers, one by each of the authors. They concern, mainly, what happens to metal when it is explosively loaded. The nature of the stress wave passing through the material and variation in shock wave due to change in standoff distance are discussed.

Cross References.

A-1-1-18 Discusses large penetrations resulting from flow in the metal after the jet itself has been consumed.

A-1-3-3 Studies the deformation of the copper cap on an explosive detonator.

B-4-43 Gives a method for investigating plastic properties of materials by impulsive-loading techniques.

B-4-55 Evaluates an equation of state for the metal using results from determination of the velocity of shock waves in aluminum.

B-4-59 Describes approximate solutions for the longitudinal impact and pressure shock problem in accordance with the Mindlin-Hermann theory.

B-4-60 Presents the results of several tests with flat tension bars of mild steel under eccentric loading.

E-2-29 Gives pin technique for measuring the free surface velocity of an aluminum target.

E-2-30 Compares properties of plastic and elastic waves in the same metal.

F-1-0-32 Discusses dislocation theory and how it applies to high-velocity working.

F-1-0-66 Describes fundamental study in the physical metallurgy of explosive forming.

F-3-0-9 Derives equations for determining power necessary to overcome the resistance of the material to forging.

G-1-0-1 Discusses plastic deformation and fractures caused by detonating an explosive charge in intimate contact with a solid body.

G-1-1-13 Points out reasons for increased hardness of steel after explosive attack.

G-1-1-14 Discusses mechanism of failure in steel caused by explosive loading.

A-3-1-14 Mentions need for making use of hydrodynamic properties which metals exhibit under high rates of forming.

## Material Behavior

### Mechanical and Physical Properties K-1

Appleton, A. S., Dieter, G. E., and Bever, M. B., "Effects of Explosive Shock Waves on a Gold-Silver Alloy", Transactions Metallurgical Society AIME, 221, 90-94 (February, 1961). K-1-1

Findings that the stored energy and hardness of the explosively-deformed alloy increased over a range of shock pressures up to 510 kbar are discussed. In the range 120 to 150 kbar there was the largest rate of increase, and markings characteristic of deformation twins first appeared. Comparison with structural changes resulting from conventional deformation processes is given.

Arnold, R. R., and Parker, R. J., "Resistance to Deformation of Aluminum and Some Aluminum Alloys", Institute of Metals Journal, 88 (Part 6), 255-259 (February, 1960). K-1-2

Resistance to compressive deformation of pure aluminum, three non-heat-treatable aluminum alloys and two heat-treatable alloys is determined by experiments on a cam plastometer. Data for strain rates from 1 to 30 inches per inch per second and temperatures of 300 to 500 C are presented.

Atkins, W., "Flash Associated With High-Velocity Impact on Aluminum", Letter in Journal of Applied Physics, 26 (1), 126-127 (January, 1955). K-1-3

By spark photography, a time history was recorded of the growth of the luminous impact flash produced by a high-velocity spherical projectile perforating an aluminum target. The spark system actually recorded only one shadowgraph per perforation, and the continuous history was obtained by recording a number of impacts with varied delay times between the instant of impact and the time the spark fired. Large fragments from the entry side of the target emerged through the flash generated on that side and were clearly visible after 250 seconds. The duration of the luminous flash was 4-5 milliseconds. Small fragments diverged radially at 60-70° to the path of the projectile and a displacement-time plot of them indicated their speed to be about 10,500 feet per second.

Bridgman, P. W., "Effects of High Hydrostatic Pressure on the Plastic Properties of Metals", Review of Modern Physics, 17 (1), 3-14 (January, 1945). K-1-4

A general qualitative description, with some test data and photographs, illustrating how ductility greatly increases with external pressure. Elongation may increase 100 times due to 30,000 Kg per square centimeter hydrostatic force on sides of a steel rod in tension. For example, the great increase of ductility under pressure appears reasonable when it is considered that the external pressure tends to prevent the formation of internal cracks from which fractures might be initiated. The increase of tensile strength under pressure might be expected in view of the closer approach of the atoms and the consequent intensification of the atomic forces. A precise theory is not developed. The phenomenon is shown experimentally to exist and a rational idea is given as to why it should.

Bridgman, P. W., Studies in Large Plastic Flow and Fracture, McGraw-Hill Book Company, New York (1952). K-1-5

The book is an extensive treatise on the effects of various stresses on plastic flow and fracture in metals. It deals primarily with the effect of hydrostatic pressure. Simple compression, two-dimensional compression, mixed compression, and tension coupled with compression are also discussed. A section deals primarily with plastic flow and fracture after prestraining.

Bridgman, P. W., "Fracture and Hydrostatic Pressure", from Fracturing of Metals, American Society for Metals, Cleveland, 246-261 (1948). K-1-6

The phenomena of fracture of metals under an imposed-hydrostatic pressure is discussed. Such theories as the Griffith crack theory and Zener's concept of abandonment of fracture-stress-curve theory are examined. Most of the theories discussed must still be supported by experiment before they may be completely accepted.

Bridgman, P. W., "Effects of High Shearing Stress Combined With Hydrostatic Pressure", Physical Review, 48 (Second Series), 825-847 (November 15, 1935). K-1-7

Mean hydrostatic pressures up to 50,000 kg/cm$^2$ combined with shearing stresses up to plastic-flow point are produced in thin disks confined between hardened-steel parts so mounted that they may be subjected to normal pressure and torque simultaneously. Qualitative and quantitative studies are made of the effects of such stresses. Among the qualitative effects it is found that many substances normally stable become unstable and may detonate, and conversely combinations of substances normally inert to each other may be made to combine explosively. Quantitatively, the shearing stress at the plastic-flow point may be measured as a function of pressure. The shearing stress at plastic flow may rise to the order of 10 or more times greater at 50,000 kg/cm$^2$ than it is normally at atmospheric pressure, that is, contrary to the usually accepted results in a narrower range of pressure. If the substance undergoes a polymorphic transition under these conditions of stress, there may be a break in the curve. This gives a very

convenient tool for the detection of transitions. Fifty-seven elements have been explored in this way, and a number of new polymorphic transitions found.

Campbell, J. D., and Duby, J., "Delayed Yield and Other Dynamic Loading Phenomena in a Medium-Carbon Steel", Proceedings of the Conference on the Properties of Materials at High Rates of Strain, Institution Mechanical Engineers (April-May, 1957). K-1-8

A description of compression-impact tests which are interpreted in terms of a criterion based on dislocation theory and which are correlated with results of constant strain-rate tension tests is presented. Dynamic stress-strain curves were obtained. Metallographic examination shows that after repeated impact the slip bands become coarser and closer in appearance than those occurring after static straining.

Campbell, J. D., and Maiden, C. J., "The Effect of Impact Loading on the Static Yield Strength of a Medium Carbon Steel", Journal of the Mechanics and Physics of Solids, 6, 53-61 (1957). K-1-9

Stress magnitude is amplified by transmitting the impact through steel rods of two cross-section changes. This amplifies the stress about two times. Strain gages are attached to the anvil bar.

Campbell, J. D., "The Yield of Mild Steel Under Impact Loading", Journal of the Mechanics and Physics of Solids, 3 (1), 54-62 (1954). K-1-10

The dynamic stress-strain curves of mild steel were obtained. The apparatus was adapted so that the steel rod which transmitted the stress to the specimen was larger than the specimen. This increased the stress transmitted into the specimen. A strain gage was attached to the specimen.

Campbell, J. D., and Harding, J., "The Effect of Grain Size, Rate of Strain, and Neutron Irradiation of the Tensile Strength of Alpha Iron", Response of Metals to High Velocity Deformation Conference, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), pp 51-76. K-1-11

A review is given of previous investigations into the effect of grain size, strain rate, temperature, and neutron irradiation on the strength of iron and mild steel. Possible explanations of their results in terms of dislocation theory are summarized. The impact apparatus used in the present work, which permits tensile testing at mean strain rates of the order of $10^3$ $sec^{-1}$, is briefly described, and the method used to derive dynamic stress-strain curves is outlined.

Test results are presented for nearly pure iron and for a special 0.21 per cent carbon steel, both in the unirradiated condition and after two different doses of neutron irradiation. These results are plotted to show the effect of grain size and strain rate on the lower yield stress, and their interpretation is discussed. Observations of brittle behavior are recorded and related to the ductile-brittle transition in mild steel.

Clark, D. S., and Datwyler, G., "Stress-Strain Relations Under Tension Impact Loading", Proceedings ASTM, 38 (Part 2), 98 (1938). K-1-12

A method of determining force-elongation diagrams for metals under tension loads is presented. The device described is called a tension dynamometer. Resistance changes were recorded on an oscilloscope. Results are given for a few steels, nonferrous metals, and alloys at a velocity of 11 feet per second. In general the yield forces under dynamic conditions were higher than those under static conditions. The maximum dynamic forces were higher than the maximum static forces. In some cases energies under dynamic loading were greater than those given by the stress-strain curve as modified by Mann. A discussion of shock waves is also given.

Clark, Donald S., "The Influence of Impact Velocity on the Tensile Characteristics of Some Aircraft Metals and Alloys", Technical Note No. 868, National Advisory Committee for Aeronautics (October, 1942). K-1-13

This report deals principally with the results of tension tests on sixteen different metals and alloys, most of which are employed extensively in aircraft construction. The tension characteristics are discussed for static conditions and rates of deformation up to about 150 feet per second.

The equipment and procedure employed in these tests are described. Velocities are obtained by means of a heavy rotating disk. The forces acting during impact are determined by means of a strain-sensitive resistance dynamometer and are recorded with a cathode-ray oscillograph. The effective constant velocity of the rotating disk permits the development of stress-strain diagrams.

It was found that magnesium and stainless steels were adversely affected by an increase in rate of deformation.

Clark, D. S., Duwez, P. E., and Wood, D. S., "The Influence of Velocity on the Tensile Properties of a Carbon Steel, Two National Emergency Steels, and a Manganese Steel", Armor and Ordnance Report No. A-241 (OSRD No. 3180), Extension of NDRC Report A-195 (OSRD No. 1641), National Defense Research Committee (January 24, 1944); ATI 24694. K-1-14

This extension of previous tests on SAE T1345 steel shows that this steel, quenched and tempered, has an upper limit of Rockwell C47 for satisfactory dynamic performances. Results of NE 8739 and NE 9445 steels show that these steels are comparable to similar SAE steels under the same conditions. SAE 1040 steel, heat treated in four different ways, shows the same results in all four states and is somewhat better in dynamic properties than SAE X1020 steel of the same hardness. This information should add some insight into the selection of steels for high-energy-rate forming dies.

Clark, D. S., Duwez, P. E., and Wood, D. S., "The Influence of Impact Velocity on the Tensile Properties of Four Magnesium Alloys and 24S Aluminum Alloy", Armor and Ordnance Report No. A-249 (OSRD No. 3256), National Defense Research Committee (February 5, 1944); ATI 225110. K-1-15

Investigations were made to determine the influence of impact velocity on the tensile properties of metals and alloys. It was found that Dow Metal M-HTA and O-1-HTA are susceptible to embrittlement by stress concentration. The energy per unit volume required to fracture these two alloys dynamically was about the same as statically when a fillet of 5 inches radius was used. The energy to fracture Dow Metal FS-1-HTA and J-1-HTA in specimens with 1/16-inch-radius fillet is higher dynamically than statically. The critical velocity of each of the four alloys is greater than 200 feet per second. Static- and dynamic-tensile tests were conducted on a 24S aluminum alloy in the "T" and annealed conditions. The tensile properties of this alloy in both structural conditions are higher when tested dynamically than statically. The values of these properties are lower for the annealed alloy and the critical velocity is greater than 200 feet per second for both conditions.

Clark, D. S., Duwez, P. E., and Wood, D. S., "The Influence of Impact Velocity on the Tensile Properties of NE 8715, NE 9415, SAE 1045, and SAE 1090 Steels", Report No. XXX, California Institute of Technology, NRC Project 82, OSRD Contract OENsr-348 (March 15, 1944); ATI 27463. K-1-16

This report gives the results of tensile impact tests on NE 8715, NE 9415, SAE 1045, and SAE 1090 steels. The two NE steels were heat treated in the manner typical of that for carburized steel. The two SAE steels were heat treated by annealing at a high temperature and a low temperature, normalizing, spheroidizing, quenching, and tempering. Of the two carburizing steels, the greatest energy-absorbing capacity was found for the NE 9415 steel. For the particular heat treatment given to the SAE 1045 and SAE 1090 steels, the former tends to have somewhat better energy-absorbing capacity than the latter. However, the spheroidized SAE 1090 steel has about the same energy-absorbing capacity as the SAE 1045 steel spheroidized. The critical velocity of both spheroidized steels is about 110 feet per second, which is the lowest obtained with any treatment.

Clark, D. S., and Wood, D. S., "The Time Delay for the Initiation of Plastic Deformation at Rapidly Applied Constant Stress", ASTM Proceedings, 717-735 (1949). K-1-17

Design and construction of a special rapid-load-testing machine is described. With this machine tensile loads may be applied to a specimen in 5 milliseconds. Tests made on an annealed low-carbon steel are presented and discussed in detail. It is shown that a definite time delay is required for the initiation of plastic deformation in this material and that this delay time depends upon the applied stress. Experimental results obtained on five materials for which the stress-strain curve does not exhibit a definite yield point are briefly presented. No time delay for the initiation of plastic deformation is observed for these materials. It is concluded that the time delay is associated with the yield point of mild steel. Rapid loading herewith refers to uniform stress whereas impact loading refers to nonuniform stress distribution.

Verbraak, C. A., Dr., "How Can High Rate Forming be Applied Without Deteriorating Metal Properties?", Paper presented at the Twelfth General Assembly of CIRP, The Hague, September, 1962, Technical Center for Metalworking, Metal Institute (TNO), Delft, Holland. K-1-18

Explosive forming increases the brittleness of a ferritic steel and lowers the stress-corrosion resistance of an austenitic steel. The influence of explosive forming on the fatigue properties of the product is not yet very well understood. The deterioration of the mechanical properties is caused by structural changes in the material which are described. In the case of austenitic steels this deterioration can be prevented by using sheet metals with definite textures. In the case of ferritic steels an increase of the distance between explosive charged and the sheet to be formed offers the only possibility to prevent a decrease in material properties. When explosive welding is used, an additional problem arises by the formation of intermetallic interlayers. A special technique based on the careful evaluation of phase diagrams, however, will provide a good weld in most cases.

Clark, D. S., and Duwez, P. E., "The Influence of Strain Rate of Some Tensile Properties of Steel", Proceedings of the ASTM, 50, 560-576 (1950). K-1-19

The inability of impact tests to reveal the true influence of strain rate on tensile properties is demonstrated. The results of static tests and tests at strain rates up to about 200 inches per inch per second are presented. The results show that the proportional limit increases to a value corresponding to the ultimate strength at a strain rate of between 40 and 80 inches per inch per second. The ultimate strength increases with increasing rate of strain up to a rate of about 100 inches per inch per second and then is not appreciably affected.

Costello, E. de L., "Yield Strength of Steel at an Extremely High Rate of Strain", The Conference of the Properties of Materials at High Rates of Strain Proceedings, Institution Mechanical Engineers (April-May, 1957). K-1-20

A method of determining the yield strength of steel at a very high rate of strain is described. The results are compared with those of other investigators and are discussed in the light of the Cottrell-Bilby theory of yielding. It is suggested that this theory is not applicable at the rate of strain involved here.

Curran, D. R., Katz, S., Kelly, J. J., and Nicholson, M. E., "Pressure Required for Transformation Twinning in Explosively Loaded Low-Carbon Steel", Transactions of the Metallurgical Society of AIME, 215 (11), 151-153 (February, 1959). K-1-21

A technique was used to measure pressure and density of the metal as a function of distance from the explosion, which was good up to a pressure of 130 kbars. Above 130 kbars there are two shock waves in the metal. At 130 kbars there may be a pressure-induced transformation in iron (alpha iron to gamma iron) which may cause heavy and light-banded regions.

Davis, R. S., and Jackson, K. A., "On the Deformation Associated With Compression Shocks in Crystalline Solids", Proceedings of the Second Symposium on Naval Structural Mechanics (1960). K-1-22

Many materials show significant changes in their properties, in particular their mechanical properties, when subjected to intense shocks. This paper outlines some preliminary considerations of deformation in strong shock and the structural changes that would accompany them.

Deshpande, R. C., and Singh, Sampooran, "Study of Slugs From Explosives With Lined Cavities", Transactions of the Metallurgical Society of AIME, 215 (3), 497-499 (June, 1959). K-1-23

The study of slugs which were recovered from shaped charges with iron liners fired into water revealed the characteristics of the microstructure of iron after undergoing extreme temperatures and pressures. The structure across a slug indicates that various temperatures from in excess of the Ac1 to below the Ac3 were obtained. However, the pressure under which the transformations took place could alter this method of temperature determination through past history considerably.

Dickinson, T. A., "Behavior of Metals Under High-Energy Loads; Explosive Forming", Tool Engineer, 40 (3), 119-122 (March, 1958). K-1-24

A general article on the behavior of metals under explosive loading.

Duvall, G. E., "Pressure-Volume Relations in Solids", American Journal of Physics, 26 (4), 235-238 (April, 1958). K-1-25

An equation of state of the form $P(V) = f(V) + Tg(V)$, which is useful for condensed matter, is proposed for the illustration of thermodynamic principles. Pressure-volume relations for adiabatic and shock compressions are derived with the assumption that specific heat at constant volume is independent of temperature. These derived relations are illustrated for a "Murnaghan" equation of state, and constants of this equation for several metals are tabulated.

Duwez, P. E., Clark, D. S., and Wood, D. S., "The Influence of Impact Velocity on the Tensile Properties of Plain Carbon Steels and of a Cast Steel Armor Plate", California Institute of Technology, Pasadena, California (March 2, 1943); ATI 25208. K-1-26

The influence of impact velocity on the tensile properties of plain carbon steels and of a cast steel armor plate is described. It is indicated that the von Karman theory as it now stands cannot be applied to materials which have a distinct yield point, that the ultimate strength of plain carbon steels is greater under impact conditions than under static conditions, and that the energy required for rupture of cold-rolled steels increases with impact velocity up to the critical value, while there may be little or no increase in the case of plain-carbon annealed steels.

Duwez, P. L., Clark, D. S., and Martens, H. E., "The Influence of Impact Velocity on the Tensile Properties of Three Gages of Furniture Steel Sheets", California Institute of Technology, Pasadena, California (October, 1949); ATI 62896. K-1-27

Results of static and dynamic tests made on samples of furniture steel sheet are presented. The purpose of these tests was to determine the effect of impact velocity on the tensile properties of sheets and to compare the results with those previously reported for ship plate. The results show that the ultimate strength of sheets, both parallel and perpendicular to direction of rolling, is increased above the static value. While the static properties of furniture steel are reasonably close to those of some ship plate, the dynamic properties are very different.

Duwez, P. L., and Clark, D. S., "Behavior of Metals Under Dynamic Conditions (NO-11) (NS-109); Influence of Impact Velocity on the Tensile Properties of Some Metals and Alloys", Office of Scientific Research and Development, NDRC (June, 1944); ATI 27496. K-1-28

A summary is presented of the results of tests made in studying the influence of impact velocity on the tensile properties of 24 ferrous and 12 nonferrous alloys. In general the dynamic tensile properties cannot be predicted from the static properties, although the order of magnitude of the critical velocity may be fairly accurately predicted on the basis of the stress-strain diagram. The ultimate strength of all material tested at impact velocities in the range of 25 to 200 feet per second is never less than the static values. The higher the static ultimate strength and percentage elongation, the lower the per cent increase of strength and elongation under dynamic conditions insofar as the ferrous alloys are concerned.

Eichelberger, R. J., "Effects of Very Intense Stress Waves in Solids", International Symposium on Stress Wave Propagation in Materials, Interscience Publishers, New York (1960). K-1-29

A discussion is presented of experimental observations on changes in resistivity of intensely stressed insulators, change in magnetic flux in moderately-stressed steel rods, modification in metallurgical structure of steel resulting from high-intensity stress, and mode of deformation of impulsively-loaded copper single crystals.

Erlifh, L. B., "The Mechanism of the Formation of Lüder's Line", The Physics of Metals and Metallography, 9 (3), 49 (1960). K-1-30

The mechanism of the formation of Lüder's lines has not so far been established. It is proposed to explain this mechanism on the basis of loss of the rigidity of thin surface layers under compression. It has been shown that in soft-steel test pieces in the process of tension, the conditions necessary for this phenomena do actually occur.

Fairlie, Jack, "Explosive Welding and Forming Open Another Door for Industry", Welding Engineer, 44 (4), 61-64 (April, 1959). K-1-31

This article describes work conducted at National Northern on the correlation of per cent elongation of materials obtainable under conventional forming techniques with the per cent elongation obtainable with high-energy-rate techniques. The relationship of $Pe = K_m f$ where Pe = per cent plasticity by explosive forces $K_m$ = a derived constant for each material and f = per cent plasticity by conventional forming was developed.

$K_m$ factors are listed as 1.0 for nickel, 1.1 for stainless steel, 1.5 for titanium, 2.3 for plain carbon steel, and 2.5 for aluminum.

Tests have been conducted on explosive-welding aluminum to aluminum, aluminum to Inconel, aluminum to stainless steel, and stainless steel to stainless steel.

It is demonstrated that, with the use of explosives, bonds between metals can be obtained without actual fusion.

Fenn, R. W., Jr., and Gusack, J. A., "Effect of Strain Rate and Temperature on the Strength of Magnesium Alloys", Proceedings of the ASTM, 58, 685-696 (1958). K-1-32

Investigation of the effect of strain rate on the strength of several magnesium alloys at temperatures up to 900 F reveals significant increases in strength with increasing testing speed. The study provides information for use in design of structures subjected to rapid loading.

Glass, C. M., Moss, Gerald L., and Goloska, Stanley K., "Effects of Explosive Loading on Single Crystals and Polycrystalline Aggregates", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), pp 115-143. K-1-33

The inception of high-pressure high-temperature operations has opened many new avenues of investigation. The authors discuss the possible effects of both on electrical resistance, ductility, hardening, and other mechanical and structural properties of metals. Phase changes in some materials at very high pressures are the basis for the production of commercial diamonds.

Ginns, D. W., "The Mechanical Properties of Some Metals and Alloys Broken at Ultra-High Speeds", Journal of the Institute of Metals, 61 (2), 61-78 (1937). K-1-34

The mechanical properties of carbon steels, copper, brasses, and aluminum alloys were investigated when broken in tension at very high speeds. The average time taken to reach the yield point is 0.001 second, and to fracture is 0.005 second. A pressure-resistance method was used for measuring stress, and a photo-cell method was used to measure strain; the two were combined to give a direct diagram on the cathode-ray oscillograph. It is shown that compared with the ordinary commercial tensile test values (a) the yield point is increased very considerably, over 100 per cent increase being recorded for some materials; (b) the maximum stress is increased by a much smaller amount; (c) the percentage elongation and the percentage reduction of area show comparatively small changes; and (d) the types of fracture are almost identical with those obtained for the slow test.

Rischer, R. B., "What are the Combined Effects of Temperature and Very High Pressures on Metals?", Journal of Metals, 12 (9), 700-702 (September, 1960). K-1-35

A discussion of experiments which were conducted on the high-velocity deformation of single-crystal and polycrystalline metals, using explosive systems to produce the loading on the metals, is presented. The results of the experiments indicate the metal properties influence the deformation, even at pressures of 300 kbars.

In single crystal studies, framing camera records show that internally loaded aluminum cylinders begin to deform nonuniformly during the first reflection of the compressive wave from the free surface. The pressures calculated in these experiments are approximately 20 kbars at the free surface, and 250 kbars at the metal explosive interface.

Copper single-crystal studies show that the deformation takes place along conventional systems, and that the deformation structures observed may be accounted for after the passage of the first compressive wave.

Several interesting structural changes in steel produced by intense pressures are discussed.

Guard, R. W., "Rate Sensitivity and Dislocation Velocity in Silicon Iron", Acta Metallurgica, 9 (2), 163 (February, 1961). K-1-36

It was conceived that the slope of the stress-velocity curve for dislocations might be determined from measurements of rate sensitivity. This note presents the results of experiments carried out to determine the validity of this method.

Harris, D. B., and White, M. P., "Comparison of the Hardening Produced in a Yield-Point Steel by Uniaxial Loading Under Static and Under Dynamic Conditions", Journal of Applied Mechanics, 21 (2), 194 (June, 1954). K-1-37

Compressive studies were made on titanium and titanium alloys from 1450 to 1725 F and at strain rates of 0.0002 to 0.01 inch per inch per second. At hot working temperatures the flow stresses of titanium alloys are markedly sensitive to strain rate. Increase of flow stress with increase of strain rate was greater for the alloys than for unalloyed titanium.

Harris, D. B., and White, M. P., "Comparison of the Hardening Produced in a Yield-Point Steel by Uniaxial Loading Under Static and Under Dynamic Conditions", Journal of Applied Mechanics, 21 (2), 194 (June, 1954). K-1-38

The theory that a yield-point metal will harden more with a given uniaxial strain under dynamic conditions than under static conditions was investigated. Low-carbon steel (0.04-0.05 C) wire, 0.100 inch diameter, in the annealed condition was subjected to strain rates of 50 fps and 0.02 ipm. The results are given in the following table:

Microhardness of Test Wires

| Specimen | VHN | Rb |
|---|---|---|
| Unstrained | 123.7 | 68.4 |
| Static | 162.4 | 82.5 |
| Dynamic | 212.0 | 93.7 |

Strain in each case was 0.055

Hendrickson, J. A., and Wood, D. S., "The Effect of Rate of Stress Application and Temperature on the Upper Yield Stress of Annealed Mild Steel", Transactions of ASM, 50, 498-516 (1958). K-1-39

The upper yield stress of an annealed low carbon steel has been determined experimentally under various constant rates of stress application ranging from about $10^2$ to $10^7$ psi per second at temperatures of -110 F and -200 F. These data are compared with two expressions derived in different ways from the dislocation theory of the distinct yield point. The three undetermined constants appearing in each of the theoretical expressions are evaluated by means of previous data on the delay time for yielding under constant stress. Both theoretical expressions are found to be in good agreement with the experimental results. This indicates that the dislocation theory provides a means for accurate prediction of the upper yield stress and the time for yielding when the applied stress varies with time in any manner.

Hendrickson, J. A., Wood, D. S., and Clark, D. S., "The Effect of Rate of Stress Application and Temperature on the Upper Yield Stress of Annealed Mild Steel", California Institute of Technology, Pasadena, California, to USA on Contract No. DA-04-495-Ord-171 (March, 1957); AD 130640. K-1-40

This report presents the results of a study on the effect of rate of stress application and temperature on the upper yield stress in an annealed low-carbon steel. An experimental investigation was made whereby the upper yield stress was determined as a function of applied stress rate within the range of from about $10^2$ to $10^7$ lb/in.$^2$ sec at temperatures of -110 F (-79 C) and -200 F (-129 C). A theoretical expression has been obtained which relates the yield stress to the applied stress rate and temperature. The expression so obtained involves several constants which are evaluated from data secured in tests to determine delay time of yielding at constant stress. The theoretical expression so obtained is found to be in good agreement with the experimental results.

Henry, O. H., and Hyatt, B. Z., "Tensile Impact Properties of Commercially Pure Titanium at Various Temperatures", Welding Journal, Welding Research Supplement, 35, 99-s-101-s (February, 1956). K-1-41

This article describes work conducted by the authors on tensile-impact testing of commercially pure titanium. Two types of titanium specimens were tested – welded and nonwelded. Of the former type, there were, first, those specimens with the welded bead intact and second, those specimens with the welded bead ground flush. The welded and nonwelded specimens were tested at the following temperatures, -65, 70, and 600 F. With the nonwelded specimens it was found that the ductility increased with temperature while the foot-pounds of energy required for fracture remained fairly constant. The energy required at all temperatures for the fracture of the welded specimens with beads intact was greater than that required to fracture those with the beads flushed.

James, H. J., Buchanan, J. S., and Teague, G. W., "The Effect of Temperature on the Dynamic Compression of Metals", Memorandum (MX) 32/59, Ministry of Supply A. R. D. E. (June, 1959). K-1-42

High explosives were used to generate shock waves in copper and mild steel at different temperatures. No change in dynamic-compression data with change in temperature was found. Some firings were done for fragment recovery, and differences in the fracture patterns are discussed.

Johansson, C. H., "Plastic Deformation and the Formation of Cracks by Detonating Charges", Ingn Vetensk Akad Tidak Tekn Forsk, 26, 16 (1955). K-1-43

This article presents a discussion of the plastic deformation and some of the fractures which may occur when an explosive charge is detonated in intimate contact with a metal. The case for a high-velocity fragment striking a solid body is also given. Several specific examples are described.

Johnson, J. E., Wood, D. S., and Clark, D. S., "Dynamic Stress-Strain Relations for Annealed 2S Aluminum Under Compressive Impact", Journal of Applied Mechanics, Transactions ASME, 20 (4), 523-529 (December, 1953). K-1-44

This paper presents the results of an experimental study of the dynamic stress-strain relations for annealed 2S aluminum. Methods of obtaining data are presented. The technique used in analyzing the data involves the use of plastic- and elastic-stress-wave propagation.

Maximum impact velocities used reached about 150 fps.

Johnson, P. C., Stein, B. A., and Davis, R. S., "Basic Parameters of Metal Behavior Under High Rate Forming", First Yearly Report, Arthur D. Little, Inc., to USA on Contract No. DA-19-020-ORD-5239 (November, 1961). K-1-45

The problem of characterizing the mechanical behavior of metals and alloys at high strain rates is basic to a quantitative analysis of high-energy-rate forming techniques and to the proper selection of the materials for forming under these conditions. The present state of knowledge in this field is confusing, contradictory, and sketchy, partially because it is difficult to obtain meaningful data in the presence of stress and strain gradients and with material constraints. The experiment described in this report shows promise as a new approach to the problem. Specifically, it involves high-speed position-time measurements of a freely expanding ring of the material under study.

Preliminary results on high-purity as-cast aluminum indicate that the increases in the stress for flow and the work-hardening rate at a strain rate of 2-5 x $10^3$ per second are substantially greater than those obtained at 2 x $10^{-3}$ per second with a standard tensile tester.

Krafft, J. M., Sullivan, A. M., and Tipper, C. F., "The Effect of Static and Dynamic Loading and Temperature on the Yield Stress of Iron and Mild Steel in Compression", Proceedings of Royal Society of London, Series A, 221 (1144), 114-127 (January 7, 1954). K-1-46

Cylindrical test samples were compressed statically and dynamically at a temperature ranging from +100 to -195 C and the yield stress, form of yield, and surface markings were observed. A Hopkinson bar and throw-off rod and electric-resistance strain gages were used for stress determination under dynamic loads.

The stress necessary to initiate yield rises steeply with fall in temperature and is accompanied by a change in mechanism of deformation from normal slip to the formation of Neumann lamellae at a critical temperature. The critical temperature is higher under dynamic loading, but there appears to be a critical stress for the formation of Neumann lamellae, whether caused by high rates of loading or low temperatures.

Kramer, A., and Baldwin, W. M., Jr., "Carbide Precipitation and Brittleness in Austenitic Stainless Steels", Transactions of the ASM, 50, 803-813 (1958). K-1-47

The ductility of the annealed steels dropped as the strain rate was increased and it increased with increase in temperature. Sensitization resulted in severe embrittlement in a critical range of low temperatures and low strain rates. Beyond this range, the ductility behavior of sensitized and annealed material was almost identical. Neither carbide precipitation nor the austenite to ferrite transformation can explain the high-speed embrittlement encountered in austenitic steels.

Krafft, J. M., "Effect of Temperature on Delayed Yielding of Mild Steel for Short Loading Duration", Transactions ASM, 48, 249-264 (1956). K-1-48

A bar-loading technique has been developed for applying uniform compressive stress for a duration of 100 microseconds and for allowing measurement of time delay before plastic yielding within this duration. With the apparatus, the relationship

between loading stress and delay time was measured for a mild steel at five temperatures in the temperature range 100 to -196 C. The results show that the loading stress increases linearly with decreasing logarithm of the delay time. The rate of increase is, however, much greater than would be anticipated from extrapolation of the similar relationships measured by Clark and Wood for loading times greater than 100 microseconds.

Kulterman, R. W., Meilson, F. W., and Benedick, W. B., "Pulse Generator Based on High Shock Demagnetization of Ferromagnetic Material", Journal of Applied Physics, 29 (3), 500-503 (March, 1958). K-1-49

The shock wave from a pellet of high explosive is passed without attenuation through one leg of a closed ferromagnetic core which has been previously magnetized. The shock wave demagnetizes the core, reducing the flux from the remnant value to zero. The change in flux generates a voltage in any winding wound on the core. Idealized calculations indicate that the voltage pulse generated in this manner will be a square wave with amplitude in volts given by $e = NB_Rvw$, and a pulse width in seconds given by $T = s/v$, where N is the number of turns, $B_R$ the remnant magnetization (webers/m$^2$) and v is the shock velocity (m/sec). It is also assumed that the core has a rectangular cross section, w being the width of the core (m) in the direction perpendicular to $B_R$ and v, and s being the thickness of the core (m) in the direction parallel to v.

Leech, E. A., Gregory, R., and Eborall, R., "A Hot Impact Tensile Test and Its Relation to Hot-Working Properties", Journal of the Institute of Metals, 83, 347-353 (1954-1955). K-1-50

Breaking tensile test-pieces at strain rates of about 250 inches per inch per second can be done at a high temperature. The behavior of copper-base materials has been compared with their known working behavior. The ductility of bronze has been compared to its liability to edge crack in hot rolling.

Leibovic, K. N., "Properties of Materials at High Rates of Strain", Metallurgia, 56 (337), 239-241 (1957). K-1-51

A general background of information is presented on the mechanisms of deformation and fracture of materials under the influence of high rates of strain. The effect of high strain rates on the yield of a wide range of materials is summarized as follows:

1. The greater the loading rate, the greater is the ratio of dynamic to static yield stress.
2. The greater the static yield, the less the strength is enhanced by rapid loading.
3. A stress greater than the static yield stress, suddenly applied and held constant, will give enhanced strength and a delay time before rapid yielding sets in.

Loizou, N., and Sims, R. B., "The Yield Stress of Pure Lead in Compression", Journal of the Mechanics and Physics of Solids, 1 (4), 234-243 (1953). K-1-52

The variation of the yield stress of pure lead in uniaxial compression with temperature, strain, and strain rate is described together with experiments designed to test the accuracy of the results. The average coefficient of friction between the platens and specimen has been measured for lubricated and unlubricated compression, and its dependence on strain rate demonstrated. The effect of previous strain rate history on the yield stress is also discussed.

Lueg, W., and Mueller, H., "Properties of Steel C45 Under Deformation Processes and as Upsetting and Shearing in Relation to Temperature and Velocity of Deformation", Archiv fur Des Eisenhuttenwesen, 28 (1782), 505 (August, 1957). In German. K-1-53

The ductility and shear strength of a steel were treated as functions of rate of deformation velocity and force. Even under elevated temperatures a work-hardening process takes place, which can be suppressed or supported by varying deformation velocities.

Minshall, F. Stanley, "The Dynamic Response of Iron and Iron Alloys to Shock Waves", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), pp 249-274. K-1-54

When a metal is subjected to a shock wave, such as that produced by the detonation of an explosive, the behavior of the shock in the metal will depend upon the dynamic properties of the metal. In particular, if the incident shock is of appropriate pressure, it will separate into a series of shocks. The first will be the fastest and weakest, the second slower and stronger, and so on. The pressures and profiles of the shock waves can be related to the dynamic properties of the metal. The dynamic-shock properties of various alloys of iron are presented in this paper.

Moss, G. L., and Glass, C. M., "Observations of the Deformation of Aluminum Subjected to Impulsive Loads of Constant Maximum Amplitude and Variable Impulse", Technical Note No. 1310, Ballistic Research Laboratory, Aberdeen Proving Grounds, Maryland (April, 1960). K-1-55

A study of four crystallographically-identical aluminum samples, each subjected to an impulsive load of equal maximum stress but different impulse, is described. It was found that aluminum deforms by the usual mechanisms even at a stress level of 270 kbar.

Moss, G. L., and Glass, C. M., "Studies of the Deformation Mechanics of an Impulsively Loaded Copper Single Crystal", Memorandum Report No. 1257, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland (April, 1960). K-1-56

It was found that copper explosively loaded with initial pressure of about 500 kbars deforms as it deforms when stressed with nonimpulsive loads. The deformation is influenced by the metal strength and structure. This is in contrast with the usual treatments of explosive strain where deformation can be treated as an entirely hydrodynamic process.

O'Brien, J., and David, R. D., "Explosive Forming Studies, Digest of Studies of Metals at Ballistic Rates of Loading", Metal Progress, 77 (4), 200 (April, 1960). K-1-57

A discussion is given of the findings of a determination of fracture stress in aluminum alloy specimens resulting from compression pulses induced by explosive loading.

Peckner, Donald, "Ultra High Pressures Create New Materials", Materials in Design Engineering, 54 (3), 111-117 (September, 1961). K-1-58

This article covers some of the research effort being conducted in the high-pressure field as well as possible applications for future products of this process. Such materials as diamond, borazon, coesite, molybdenum carbide, and tantalum nitride have been prepared by this technique. It is theorized that it will be possible to squeeze an atom so hard that its outermost electrons are forced into vacant inner shells thereby creating new materials. Pressures up to 400,000 atmospheres have been reached by some researchers in this field.

Rabinowicz, E., "Metal Transfer During Static Loading and Impacting", Proceedings of the Physical Society of London, 65 (Series B), 630-631 (August, 1952). K-1-59

Experiments are described which investigate the metal transfer which takes place when a radioactive hemispherically-ended slider is pressed normally into a flat surface of the same or another metal. It is found that metal transfer in the form of a number of small fragments is always observed, and this supports the view that metallic junctions are formed between metal surfaces in contact. Experiments in which a load is varied suggest that at the higher loads the oxide layer on the metal surfaces is broken up to a larger extent than at lower loads, and a more than proportional increase in metallic interaction and transfer takes place. An analogous effect is observed in the presence of boundary lubricants. When the surfaces are impacted together, very similar results are obtained. Somewhat less pick-up is observed than for static loading, and the difference is probably due to the fact that it takes time for strong junctions to be formed. Impact experiments with surfaces covered by lubricants show that a lubricant layer may be trapped between the surfaces, and this produces a large reduction in pick-up without greatly reducing the amount of plastic deformation.

Rinehart, J. S., "Deformation of an Explosively Loaded Aluminum Single Crystal", Journal of Applied Physics, 26 (11), 1315-1318 (November, 1955). K-1-60

A hollow cylindrical single crystal of pure aluminum was deformed by detonating an explosive charge that had been placed axially within the crystal. The approximate strain rate achieved was 105 inches per inch per second. The object of the test was to relate the pattern of deformation to the stresses set up by the explosive and the crystallographic axes of the crystal. The reaction of the cylinder was markedly different from the reaction which would be exhibited by a similarly shaped cylinder of polycrystalline material. The deformation was nonuniform with both the fracturing and the plastic flow exhibiting a twofold symmetry that could be unambiguously related to the orientation of stress with respect to the crystallographic axes and their associated slip systems.

Roberts, D. K., and Wells, A. A., "The Velocity of Brittle Fracture", Engineering, 178 (4614), 820 (December, 1954). K-1-61

In the propagation of Griffith-type cracks, the balance of energy should contain terms relating to the available elastic energy, the surface tension, and the kinetic energy of the material disturbed by the progressing crack. The terminal velocity of a freely running-brittle crack is calculated to be 38 per cent of the elastic wave velocity, which is in good agreement with experimental results.

Sakui, S., and Omori, M., "Behavior of Pure Iron Under Impact Tensile Loading", Tetsu To Hagane, 45 (4), 415 (April, 1959). In Japanese. K-1-62

Under impact-tensile loading, yield stress and tensile strength were found to be larger and total elongation smaller than under static test. At high strain rates, both yield stress and tensile strength increased while total elongation decreased slightly.

Ida, N., and Burkhart, J., "Metallurgical Effects on Residual Properties of Explosively Formed 2014 Aluminum Alloy", Report No. R-61-7, The Martin Company, Denver, Colorado (May, 1961). K-1-63

The general metallurgical effects associated with high-energy-rate metal forming of the 2014 aluminum alloy have been investigated. Changes in microhardness, strength, draw-to-bulge ratios, and microstructures with maximum deflection have been correlated. The conclusions of this report were as follows:

(1) The over-all reliability (in terms of mechanical strength and ductility) of a part formed by explosive forming is restrictive in the smaller die sizes because of the high degree of scatter in data derived. This scatter diminishes with larger size.
(2) Microstructural changes accompany this type of forming process as evidenced by grain-boundary widening and second-phase agglomeration. However, the studies are insufficient to determine the effect of this change on the over-all properties of 2014.
(3) The 2014 aluminum alloy, especially in the larger die sizes, responds favorably to high-energy-rate forming of domes.
(4) The general increase in hardness and strength of the parts formed by explosives does not appear to affect the residual ductility of the 2014 alloy.

The data was obtained in work conducted on hemispherical and elliptical sections.

Shurakow, S. S., "The Effect of Deformation Rate on the Ductility of Hardened Steel", Metallovedenie i Obrabotka Metallov, 10, 57-63 (October, 1956). In Russian. K-1-64

Tests show that ductility in hardened steels increases with a higher rate of deformation, and brittleness is lessened.

Tardif, H. P., and Erickson, W. H., "Explosive Metallurgy", Canadian Mining and Metallurgical Bulletin, 51 (554), 352-359 (June, 1958). K-1-65

This paper gives a brief history of the use of explosives in industry; shaped charge uses, cartridge forming of thin materials in a die, and a comparison of static and dynamic deformation of a steel block with a steel stud are discussed. Tables are presented for static- and dynamic-physical properties of several steels, two aluminum alloys, and copper. Photographs of unusual grain structure, test equipment, and test articles are presented.

Taylor, G. I., and Whiffin, A. C., "The Use of Flat-Ended Projectiles for Determining Dynamic Yield Stress", Proceedings of the Royal Society of London, 194 (Series A), 289 (1948). K-1-66

The deformation of a flat-ended projectile, due to being fired at high velocity against a steel plate, is used as a measure of the dynamic yield stress of the projectile. In Part I the theory of the method is presented. Results of experimental tests are shown in Part II. Satisfactory results were obtained for velocity of impacts from 400 to 2500 feet per second.

Taylor, D. B. C., "Non-Uniform Yield in a Mild Steel Under Dynamic Straining", Proceedings of the Conference on the Properties of Materials at High Rates of Strain, Institution of Mechanical Engineers (April-May, 1957). K-1-67

A detailed description of the apparatus is given. The experimental results are discussed, and it is shown that initiation and propagation of nonuniform yield are described by one criterion. Hence, they do not seem to be two separate phases of dynamic straining.

Uzlik, G. V., and Voloshenko-Klimovitsky, J. J., "On the Elastic-Plastic Strain of Steels Under Longitudinal Impact", Proceedings on the Conference of the Properties of Materials at High Rates of Strain, Institution of Mechanical Engineers (April-May, 1957). K-1-68

A study of the initial stage of plastic strain of metals under longitudinal impact was given. The evaluation of the metal's resistance to initial plastic deformation is of prime importance when elucidating the strength conditions in the zones of stress concentration. Methods which determine the metal's resistance to initial yielding are given.

Vigness, I., Krafft, J. H., and Smith, R. C., "Effect of Loading History Upon the Yield Strength of a Plain Carbon Steel", Proceedings of the Conference on the Properties of Materials at High Rates of Strain, Institution of Mechanical Engineers (April-May, 1957). K-1-69

Yield strength has been measured for three different patterns of load application. A delay-time, characteristic of each pattern of loading, elapses between the attainment of the static upper yield stress and the dynamic yield. Accrual of damage in direct proportion to time of loading is a valid approximation from measurement of the effect of short time per yield loads on the constant-stress delay time.

Volkogon, G. M., "Effect of Deformation Rate on the Mechanical Properties of Nickel at Elevated Temperatures", Metallovedenie i Termicheskaya Obrabotka Metallov (4), 46-47 (April, 1960). In Russian. K-1-70

Tensile-impact tests of specimens from 600 to 1100 C and at 2 to 420 millimeters per second are discussed in terms of tensile-impact strength, reduction of area, plasticity and deformation rate, and temperature. Results do not agree with the general opinion that with increase of deformation rate, plasticity should be decreased.

White, M. P., "On the Impact Behavior of a Material With a Yield Point", Journal of Applied Mechanics, ASME Transactions, 71, 39-52 (March, 1949). K-1-71

This article is a continuation of the work done by Duwez and Clark and concludes that under impact the material with a definite yield point is made harder and ruptures at a higher stress and smaller strain than when loaded statically. The critical-impact velocity defined as that at which nearly instantaneous failure occurs in tension is discussed, and factors on which it depends are given. Many curves and formulae are given to illustrate the point.

Wood, D. S., and Clark, D. S., "The Influence of Temperature Upon the Time Delay for Yielding in Annealed Mild Steel", Transactions of the ASM, 43, 571-586 (1951). K-1-72

The results of an experimental investigation of the time required for the initiation of plastic deformation in an annealed low-carbon steel, subjected to rapidly applied tensile stress at four temperatures, are presented. The stress is applied to a test specimen in a continuous manner within a period of 7 milliseconds and is maintained substantially constant thereafter. The extension of the specimen is measured as a function of time.

A well-defined period of time is found to elapse between the instant the stress reaches its full value and the instant plastic deformation begins. This time is designated as the delay time. The delay time is measured as a function of the applied stress at temperatures of -75, 73, 150, and 250 F. At any given temperature the relation between the logarithm of the delay time and the applied stress is represented by two connected straight lines. One is a line of constant stress; the other is a line which the delay time decreases as the stress is increased to values above the constant stress line.

The line of constant stress is identified with the static upper yield stress of the material.

Zener, C., and Holloman, J. H., "Plastic Flow and Rupture of Metals", Transactions of ASM, 33, 163-215 (1944). K-1-73

This paper constitutes an attempt to coordinate and interpret the present knowledge of the plastic flow and rupture of metals. Some of the data found in the literature required the introduction of new concepts for their explanation. New models have been suggested which appear to better coordinate the existing knowledge in this broad field. Two systems have been in common use for specifying (a) the conditions for the initiation of plastic flow, (b) the precise nature of flow under a given stress pattern, and (c) the relation between the strain hardening occurring in different types of flow. In this paper these two systems are discussed in detail, and a comparison is made between their predictions and the experimental observations. A new theoretical treatment is given of the application of these systems to the problem of strain hardening.

Zener, Clarence, "The Intrinsic Inelasticity of Large Plates", The Physical Review, 59 (Second Series), 669-673 (January 1-June 15, 1941). K-1-74

A theory is developed for the reaction of plates to forces of such short duration that the waves reflected from the boundary may be neglected. It is found that the velocity of the point of application of the force is proportional to the force, and hence the total displacement is proportional with large plates. The coefficient of restitution is obtained as a function of the parameters of the impact. Complete agreement is obtained with previous experiments.

Abbott, K. H., "Metallurgical Observations of High Velocity Impact", Technical Report No. WAL TR 161.85/1, Watertown Arsenal Laboratories (September, 1960). K-1-75

Annealed 1020 steel, hardened FXS-318 steel, and 2024-T4 aluminum-alloy pellets with length-to-diameter ratios of 1.25 were fired at standard steel armor, aluminum armor, and 301 stainless steel plates at velocities from 2,000 to 13,000 fps. Plate sections containing crater half-sections were subjected to hardness, macrostructure, and microstructure measurements to determine metallurgical phenomena which influence crater formation. Dynamic instabilities resulting in slip with the formation of transformed untempered martensite on maximum shear planes were observed in the standard steel armor. The number of these shear bands with associated cracking increased with increasing pellet velocity. Slip without transformation was observed in both the aluminum alloy and stainless steel plates. No local transformation from austenite to martensite was observed in the stainless steel. Extensive hardening in the vicinity of the crater was measured in all plate materials.

Beyer, W. K., "Behavior of Materials Under Conditions of Explosive Stressing", Report No. AN-61-AMR-8024, General Dynamics Astronautics, San Diego, California (December, 1961). K-1-76

This report covers the investigation conducted at General Dynamics Astronautics to determine the maximum strain that a material can withstand without rupturing by explosive loading. The materials which were selected for this program are the basic types presently used in the missile industry. Evaluation of tooling materials for hydrochemical forming was also initiated. Of the several dies designed and fabricated the most unique proved to be the shell die backed by water. It was concluded that the full physical and metallurgical properties of stainless steel formed by explosive forming could be utilized. The correct sizing and placement of the explosive charge would result in minimized springback. It was found that the forming of titanium and its alloys by explosive forming could be conducted at elevated temperatures.

Fields, D. S., Jr., "Shaping and Forming", Journal of Metals, 12 (3), 237 (March, 1960). K-1-77

The author mentions that ductility and formability of a material is improved by forming it explosively rather than conventionally. Little work has been done in determining what causes this improvement so it is difficult to say whether it results from the dynamic effects of explosive loading or from the lack of frictional restraints between the workpiece and the die.

Poczatck, Joseph J., and Fugelso, L. E., "A Theoretical Study of Response of Solids to Impulsive Loads of High Pressure", Final Report, American Machine and Foundry Company to USAF on Contract No. AF 29(601)-2533 (October, 1961). K-1-78

The response of materials and structures to pressures on the order of one megabar is considered. The problem is decomposed according to the characteristic response time for various failure modes. The short-time-effects study analyzes propagation of these high pressure pulses. General equations are developed for a solid under finite strain, with dissipation mechanism, heat conduction, and elasticity coefficients open to specification. Integral equations following motion of nonisentropic waves are obtained for uniaxial strain.

The long-time-effects study develops dynamic elastic-plastic-deformation theory of solids utilizing dislocation theory. Continuum equations for the elastic-plastic displacements and stresses are derived.

<u>Cross References.</u>

B-4-7 Gives equation of state data obtained by impacting copper with a copper projectile.

B-4-26 Discusses propagation of compressive waves generated by high explosives. The waves were characterized by abrupt and possibly quasi-discontinuous changes of pressure.

B-4-29 Describes the determination of the equation of state of burned explosive gas by calculating the attenuation of the shocks.

B-4-30 Discusses the determination of the equation of state of burned explosive gas by calculating the attenuation of the shocks.

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| B-4-35 | Gives equations of the shock transition as methods for measuring the equations of state of solids with shock waves. |
| B-4-61 | Reviews the static and dynamic response of materials to stress. |
| B-4-62 | Measures transit times for the passage of a shock wave through plates. |
| E-2-5 | Interprets force-time curves obtained from measurement of forces acting on a specimen during a tension impact test. |
| E-2-17 | Presents equations of state for iron alloyed with nickel and/or chromium. |
| E-2-24 | Investigates mechanical properties of materials at high rates of loading. |
| F-1-0-42 | Discusses how physical properties are changed by forming with high explosives. |
| F-1-0-52 | Reports comprehensive metallurgical tests to determine the effects of high-energy-rate forming on certain materials. |
| F-1-1-5 | Gives mechanism for "velocity impact hardening". |
| F-2-1-1 | Evaluates variable parameters of energy level, inductance, initiation-wire material, diameter and length, gap distance, standoff distance, and liquid medium relative to current, pressure, and deformation work. |
| G-1-1-2 | Investigates effect of high dynamic pressures generated by strong shock waves on the metallurgical properties of steels. |
| G-1-1-3 | Describes work accomplished by explosively loading a wedge of 1020 steel. |
| G-1-1-4 | Investigates the general response of metals and alloys under very high strain rate loading. |
| G-1-1-6 | Shows that the hardness to yield strength ratio is less for explosively hardened materials than for normal work-hardened materials. |
| G-1-1-7 | Discusses technique of "velocity impact hardening" and its effect on the material. |
| G-1-1-8 | Shows that effect of adiabatic straining (as in explosive forming) is to produce a fine and diffuse slip. |
| G-1-1-9 | Discusses specimens of austenitic manganese steel which were subjected to shock action in an arrangement which produced uniaxial compression in a shock front followed by essentially uniaxial expansion. |
| G-1-1-10 | Investigates shock-deformed pearlite in 1020 steel. |
| G-1-1-12 | Gives hardness measurements made along radii of circular cross sections of an annealed, thick-wall, low carbon steel cylinder internally loaded with an explosive charge. |

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| G-1-1-17 | Discusses quantitatively the increase in hardness by explosive hardening; also the increase in yield and tensile strength. |
| G-1-1-20 | Discusses the physical properties of iron-base alloys after explosive impact. |
| G-1-2-1 | Gives pressure-compression curves for 27 metals. |
| G-1-2-5 | Covers work performed on measuring the mechanical properties of explosively impacted iron and titanium alloys. |
| H-0-2 | Covers the influence of explosive charges on the materials being worked. |
| J-3-3 | Investigates mechanism of plastic deformation and fracture caused by high explosives. |
| J-3-5 | Suggests new types of experiments to yield information on pulse shapes and on some of the dynamic properties of materials. |
| J-3-6 | Suggests new types of experiments to yield information on pulse shapes and on some of the dynamic properties of materials. |
| J-3-7 | Studies scabbing from a phenomenological point of view. Compares implications of both elastic and elastoplastic analyses. |
| J-3-8 | Analyzes stress states which can cause scabbing. |
| J-3-9 | Presents contour method for analysis of scabbing. |
| K-2-6 | Discusses smooth spalling of Armco iron when subjected to shock waves. |
| K-2-8 | Investigates effect of high dynamic pressures on the metallurgical properties of iron and titanium alloys. |
| K-2-18 | Deals with changes in microstructure and microhardness and types of fracture produced in steel targets subjected to high velocity impacts. |
| K-3-20 | Investigates tensile strength, yield strength, and breakage energy of specimens subjected to high-velocity impacts. |
| K-3-22 | Plots energy/unit volume absorbed by copper (struck by high-velocity steel projectiles) versus strain and computes true stress-logarithmic strain curve. |

## Material Behavior

### Structure K-2

Caisso, J., and Micard, J., "Contribution to the Study of the Propagation of Luders Lines in Solid Solutions", Memoires Scientifiques de La Revue de Metallurgie, 57, 57-61 (January, 1960). In French. K-2-1

The influences on test results of the dimensions of tensile test specimen, temperature, and localization of the rupture point are discussed. The oscillograph record shows sudden decreases of stress due to temperature variations.

Campbell, J. D., Duby, J., and Puttick, K. E., "Metallography of a Medium Carbon Steel Subjected to Slow and Impact Compression", Philosophical Magazine, 2 (16), 548 (1957). K-2-2

Specimens of medium carbon steel subjected to slow and dynamic compression have been examined by optical and electron microscopy. In slow deformation, coarse slip in ferrite occurs in very narrow regions on corrugated surfaces; this behavior appears to be related to the presence of an aging precipitate. Coarse slip is absent in rapidly strained steel; the metal deforms by fine slip which occasionally forms deformation bands.

Campbell, J. D., Simmons, J. A., and Dorn, J. E., "On the Dynamic Behavior of a Frank-Read Source", Minerals Research Laboratory, Institute of Engineering Research, University of California, Berkeley (May 15, 1959). K-2-3

This report covers the development of theory of dislocation motion under the influence of impulsive loading. A complete solution is given for the nonrelativistic activations of a dislocation half-mil under shock stressing in the absence of viscous forces. A partial solution is given for the relativistic activation of a dislocation half-mil. A typical Frank-Read source is shown to begin to multiply about $5 \times 10^{-10}$ seconds when the plastic strain is about 0.003.

Clark, G. B., and Bruckner, W. B., "Behavior of Metal Cavity Liners in Shaped Explosive Charges", AIME Transactions, 176, 527-540 (1948). K-2-4

This article deals with the effect of explosive forming on the microstructure of cast iron.

Dieter, G. E., "Metallurgical Effects of High-Intensity Shock Waves in Metals", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), p 409-445. K-2-5

A discussion of the changes in microstructure and microhardness of chromium and nickel produced by high-intensity shock waves of explosive origin are given. It was found for columbium that the hardness increases nearly linearly with pressure over the same range in which there is a sharp discontinuity in hardness and microstructure in iron. The microstructure of columbium contains mechanical twins which increase in number with increasing shock pressure.

The changes in microstructure and microhardness produced in nickel by the passage of high-intensity shock waves have been investigated over the range of pressure from 100 to 620 kbars. Detailed examination of the slip-band structure with the electron microscope revealed that explosively-hardened nickel is deformed into third stage slip. Explosively-hardened nickel has a lower slip-band density than nickel hardened to the same degree in slow-speed compression but there is a greater amount of slip on each slip band.

Erkman, J. O., "Smooth Spalls and the Polymorphism of Iron", Poulter Laboratories Technical Report No. 012-60, Stanford Research Institute, Menlo Park, California (December 16, 1960). K-2-6

A smooth fracture may be observed when Armco iron is caused to spall. Smoothness of the spall is here attributed to the particular shape of the wave transmitted by iron to the phase transition at 0.131 megabar. When transient pressure waves greater than 0.131 megabar are induced in iron, two distinct shocks are transmitted. These shocks are followed by a steep rarefaction which may be called a rarefaction shock. When a free surface is encountered, the first shock is reflected as a backward-facing rarefaction wave. This wave may also steepen into a rarefaction shock which eventually meets the forward-facing rarefaction shock. This interaction results in a localized tension of destructive magnitude which produces a smooth fracture. Location of the plane of this intersection was calculated by applying the theory of hydrodynamics.

Franz, R. E., "Experimental Study of Magnetic Effects in Steel Under Explosive Loading", Report No. 1353, Aberdeen Proving Ground, Maryland (June, 1961); AD 262638. K-2-7

Experimental findings on the changes in magnetic flux in steel rods which underwent explosive loading are given. The data were correlated with the stresses produced by such loading.

Pressure profiles were calculated by integration of the signals obtained from search coils. These values of pressure turn out to be extremely low at distances of 10.8 and 22.8 cm down the rod, reaching a maximum of only 5-6 thousand psi, as compared to values of pressure obtained by pin measurements at the same points. Pin measurements indicate pressures almost ten times the magnitude of those calculated from magnetic effects. The magnetic measurements are consistent within themselves since, at different initial-flux densities the pressures deduced are approximately the same.

Wilsdorf, Doris, "Point Defects and the Plastic Behavior of Metals", Metals Review, 32 (12), 11 (December, 1959). K-2-8

The overriding importance which the dislocation type of lattice defect has for the plastic properties of metals has been fully recognized for the past quarter of a century. Consequently, much research has been done to investigate the properties of dislocations, as well as their interaction with each other, with impurities in solution and in the form of precipitates, with grain and sub-boundaries, with surfaces, internal stresses, conduction electrons and heat motion. Now it appears that thermal vacancies and interstitials are more important for the understanding of the plastic behavior of metals than many of the named entities. More thorough investigation into their properties and their effects on dislocations are being conducted, and some interesting results are now available bearing on the phenomena of quench hardening, irradiation hardening, work hardening, fatigue, diffusion under stress, and age hardening.

Johnston, W. G., "Properties of Individual Dislocations", Metals Review, 32 (12), 8 (December, 1959). K-2-9

This article describes research work in studying dislocations in crystals by etch, pit, decoration, X-ray, and electron microscopic procedures. Four ways to originate the first dislocation in a crystal are: surface damage; inclusions; precipitates; and the effect of solidification and nucleation by very high stresses (1,000,000 psi).

Moss, G., and Glass, C., "A Study of the Relationship Between the First Compressive Stress and Gross Plastic Deformation in Explosively Loaded Copper", Memo Report No. 1236, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland (September, 1959); PB 145014. K-2-10

A single crystal of copper in the form of a hollow cylinder was subjected to an internal explosion. Analysis of pictures showed that slip and kink bands are not associated with the initial intense compression front but develop later and indicate atomic movements that result in the final shape of the specimen.

Moss, G. L., and Glass, C. M., "An Investigation of the Structure of Copper After Exposure to Very Intense Stress Waves", Memorandum Report No. 1248, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland (February, 1960). K-2-11

X-ray-diffraction techniques were used to examine an explosively-loaded copper single crystal for presence of macrotwins and kink bands. The results did not indicate the presence of mechanical macro-twins, but kink bands which are commonly found in slowly deformed copper were found.

Moss, G. L., and Glass, C. M., "Some Microscopic Observations of Cracks Developed in Metals by Very Intense Stress Waves", Technical Report No. 1310, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland (1960); AD 237943. K-2-12

Explosively-induced stress waves were propagated through various metals so that scab-type fractures resulted. Microscopic examinations were then made of the metal

adjacent to the fracture surfaces. In each case, the fractures began at imperfections within a thin plate of metal that was parallel to and included the observable fracture surface. The thickness and position of this plate within the metal appears to be a function of the inclusions present, subboundaries, and crystal orientation.

It is concluded that these metallurgical factors influence the response of metals even under explosive loading.

Pond, R. B., and Glass, C. M., "Crystallographic Aspects of High Velocity Deformation of Aluminum Single Crystals", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York, New York (1961), p 145-161. K-2-13

Thirty single-crystal specimens were extended in tension at strain rates varying from 36 to 2000 ips and the resultant specimens were examined by optical and X-ray techniques. The probable existence of a von Karman critical velocity is deduced from the data using the Hoppmann (or velocity-vs-elongation) technique. Certain crystallographic aspects of deformation as a function of velocity are developed. The role of orientation in high-velocity deformation is discussed.

Riabinin, Iu. N., "Certain Experiments on Dynamic Compression of Substances", Soviet Phys. Tech. Phys., 26 (12), 2661-2666 (1956). K-2-14

A description is given of a dynamic method of compressing a substance to pressures of several hundred thousands of atmospheres. Exploratory experiments have shown that, on rapid compression and expansion, intrinsic irreversible changes occur in some substances. Experiments are described on strong compression of graphite at very high temperature. In spite of these experiments being carried out in the region of pressures and temperatures at which diamond is stable, diamond was not produced because of the slow rate of transformation.

Roberts, J. M., and Gow, K. V., "Deformation of Single Crystal of Aluminum", Transactions of Metallurgical Society of AIME, 212 (5), 648-658 (October, 1958). K-2-15

Single crystals of aluminum for single slip and duplex slip were deformed at 23,000 psi and 600 C at creep, normal, and very rapid rates of straining. A study of the crystallography of deformation was made by optical examination of slip traces.

Rossard, C., "Contribution to the Study of Hot Plastic Deformation of Steels", Metaux Corrosion-Industries, 35 (417), 190-205 (May, 1960). In French. K-2-16

Development of strain and torque in 0.25 per cent carbon steel and 25 per cent chromium ferritic steel at constant and changing temperatures between 900 and 1200 C are presented. Influence of amount and rate of deformation, temperature, and holding material at deformation temperatures after removal of stress on structure and grain size is discussed.

Singh, S., Soundiaraj, A., and Deshpande, R. C., "Studies of Slugs From Explosives With Lined Cavities I and II", Transactions of AIME, 215 (1), 166-168 (February, 1959) and 215 (3), 497-499 (June, 1959). K-2-17

Part I: Metallographic examination of copper slugs formed from firing shaped charges into water was conducted. The apex of the slug was heavily deformed and twinned. In an intermediate zone there was an area partially recrystallized with some evidence of twinning. The center was completely recrystallized and evidence of a temperature gradient from the apex to the center was found. A hardness traverse revealed extreme hardening of the outer heavily-worked area decreasing to a normal level at the center.

Part II: This part dealt with the same observations in low-carbon steel (1020) slugs. In general, the same characteristics were noted.

Singh, S., and Gandhi, P. M., "Effects Produced by Explosives With Lined Cavities in Steel", Research (London), 9, 55-61 (February, 1961). K-2-18

This article deals with the changes in microstructure and microhardness and the types of fracture produced in massive steel targets by jets squirted from high explosives with copper-lined conical cavities.

Singh, S., Krishnaswamy, N. R., and Soundraraj, A., "Hardness Plateaus and Twinning in Steel by Explosives With Lined Cavities", Journal of Applied Physics, 27 (6), 617 (1956). K-2-19

This article deals with the effect of metal jets squirted from explosives with lined cavities on the microhardness, microstructures, and types of fracture produced in massive medium-carbon steel targets.

Smith, Cyril Stanley, "Metallographic Studies of Metals After Explosive Shock", Transactions of the Metallurgical Society of AIME, 22 (5), 574-589 (October, 1958). K-2-20

Investigations were conducted on the effect of explosive shock waves on the physical characteristics of materials. Copper after shocks of above 200 kbars shows numerous mechanical twins, which make no significant contribution to the hardening. They occur most frequently at angles of 30 degrees to the rarefaction direction and do not appear in the zone where rarefaction is the steepest. Iron, conversely, develops Neumann bands on compression and above 150 kbars undergoes a transition to a different phase, which after return to atmospheric pressure leaves a complex microstructure reminiscent of carbon-free martensite.

Smith, Cyril Stanley, and Fowler, C. M., "Further Metallographic Studies on Metals After Explosive Shock", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Intersciences Publishers, New York (1961), p 309-341. K-2-21

New studies of the position of the interaction between first-shock rarefaction and second shock in iron agree closely with predictions from the Hugoniot curve and are almost independent of specimen thickness from 1.5 to 38 millimeters.

In single crystals of copper after 300 kbars plane shock, deformation twins are shown to occur only on (111) planes and not on those planes inclined at very small or large angles to the shock direction. A crystal shocked in the (100) direction, however, showed no crystallographic markings whatever and had obviously suffered deformation by a mechanism different from the others. It recrystallized completely at 155 C while crystals of other orientations recrystallized only at a distance from the free surface, indicating a relationship between the steepness of the rarefaction front and the residual strain energy.

Soper, William G., and Potteiger, Lester A., "Explosive Induced Pressures in Iron", NWL Report No. 1786, NAVWEPS, Report No. 7669, U. S. Naval Weapons Laboratory, Dahlgren, Virginia (November 22, 1961); AD 267025. K-2-22

A metallographic technique is discussed for determining the level of pressure to which iron plates have been subjected by explosive loading. The interaction of the shock and rarefaction waves within the plate is analyzed to arrive at formulas from which the intensity of pressure can be determined when the velocity of the detonation front is known. This technique is employed to determine the pressure induced in iron by oblique detonation of four common explosives of compositions B, C-3, C-4, and H-6.

Strohecker, Daniel E., "Explosive Impact Studies of H-11 Material and Weldments", NA61H-43, North American Aviation, Columbus (May 12, 1961). K-2-23

A study of the effects of direct-contact explosive charges on the properties of H-11 (5 per cent chrome die steel) was undertaken. It was found that the use of contact explosive on H-11 steel causes brittle failure in the heat-treated condition of the material (280-300 ksi). It was also found that severe deformation and distortion of parts even when backed up with steel tooling would result from contact charges. The metallurgical structure of the material after impact indicated the presence of a very hard white phase which reacted to heat treatment in a manner similar to martensite.

Tardif, H. P., "A Review of CARDE Activities in the Field of High Rates of Loading", CARDE Technical Memo No. 253/59 (July, 1959), Paper presented at OOR Conference on High Rates of Loading, Duke University, March 25-26, 1959; AD 230804. K-2-24

A determination of hardness increase by slow and fast deformation rates was made. The findings of the study indicated that under the method of deformation used the hardness was always higher in the statically deformed than in the dynamically deformed specimens both in the unaged and the aged condition. Tensile test results also corroborated the hardness test results.

The results of some explosive-forming studies are also discussed. It was found that when the forces required to deform a cone by "gathering" in the conical orifice (the forces of deformation plus the frictional forces) becomes too large, the shape formed stops moving and its front end is then deformed further by deep-drawing. Studies were conducted on type 304, 316, 321 stainless steel, 1100-H14, and 6061-T6 aluminum.

Tardif, H. P., "H. P., "Metallurgical Activities at CARDE", Canadian Mining and Metallurgical Bulletin, 49 (529), 372-376 (May, 1956). See also Canada Metals, 19 (10), 42, 44-45 (October, 1956). K-2-25

This article deals with the flow of metal in steel blocks perforated by a shaped charge; metallographic observations of its effect on the structure surrounding the perforation are reported. It deals also with "adiabatic" fracture.

Tardif, H. P., Claisse, F., and Chollet, P., "Some Observations on Explosively Loaded Iron and Mild Steel", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), p 389-407. K-2-26

Cylindrical single crystals of iron were explosively loaded at one end by means of tetryl pellets. At distances 5 millimeters or more from the impacted surface the deformation markings observed were identified as Neumann bands and it is shown that they obey the conventional laws of twinning. The main markings observed immediately under the impacted surface also have the same orientation as those away from the dark-etching zone, and it is believed they are also mechanical twins, contrary to previously proposed theories.

No relationship between the number of twinning directions and hardness plateaus was observed as proposed previously. The number of twins, however, decreased proportionately to hardness from one end of the crystal to the other.

Weertman, J., "High Velocity Dislocations", Response of Metals to High Velocity Deformation Conference, AIME, Estes Park, Colorado, July 11-12, 1960, Interscience Publishers, New York (1961), p 205-247. K-2-27

The theory of moving dislocations is reviewed, with an emphasis on dislocations in uniform motion. Eshelby's analysis of an edge dislocation moving in an isotropic medium is extended and it is shown that, contrary to the usual situation, edge dislocations of like sign attract each other (unlike repel each other) when the dislocations are traveling at velocities above the Rayleigh wave velocity (approximately 0.9 times the transverse sound velocity).

Cross References.

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| B-4-28 | Reports dynamic theory for the explosive production of multiple shocks in metals which undergo a phase transition. |
| B-4-35 | Shows how phase transitions in materials give rise to multiple shock waves. |

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| F-1-0-97 | Shows effects of explosive forming tests on microstructure. |
| G-1-1-15 | Discusses formation of Neumann bands by shock loading and mentions that shock pressures above 130 kilobars produce a polymorphic transformation in iron. |
| G-1-1-19 | Discusses changes in microstructure brought about by explosive loading. |
| H-7-1 | Shows that new phases are formed by explosive welding with the lowest melting constituent being the base metal. |
| K-1-29 | Reports experimental observations on modification in metallurgical structure of steel resulting from high-intensity stress. |

## Material Behavior

### Stress-Strain Relation K-3

Backman, Marvin E., "Impact", NOTS TR 2367, U. S. Naval Ordnance Test Station, China Lake, California (January 19, 1960); AD 231041. K-3-1

A general look at the effects of impact by moving projectiles is given. A comparison of such impacts with the results of meteorite impact provides some indication of the energies involved in such processes. Descriptions of the characteristics of high-velocity impacts by variously shaped projectiles and the material behavior of both the projectiles and the targets are presented.

Baldwin, William M., Jr., "Why Metals Fail", Metals Review, 32 (12), 10 (December, 1959). K-3-2

The four types of failures associated with embrittlement are discussed. The loss of ductility due to strain-rate sensitivity is a function of temperature, strain rate, and the metal. Low-carbon steels are not affected to the extent that austenitic stainless steels are. Hardened surfaces tend to promote brittle failure by initiation of cracks in the hardened surface which propagate into the softer material.

Baron, H. G., "Effect of Strain Rate on the Tensile Stress-Strain Characteristics of Metals", Metal Treatment and Drop Forging, 12 (6), 25-30 (January, 1962). K-3-3

In this review the author's work using strain rates of $10^{-3}$ and $10^{2}$ inches per inch per second is used as the basis for discussion. Attention is drawn to several features in this and other investigations which may have practical importance in metalworking. For example, yield-point phenomena and twinning in the softer steels, adiabatic effects, and variations in energy absorption and ductility with rate of strain are discussed. The concept and application of critical-impact velocity are also outlined.

Baron, H. G., "Stress-Strain Curves of Some Metals and Alloys", Journal of the Iron and Steel Institute, 182, 354-365 (April, 1956). K-3-4

Comparative tensile tests were carried out on a number of metals and alloys at different temperatures and strain rates. The strain rate and temperature have a marked effect on iron and soft ferritic steels. Both aluminum alloys and copper are affected while annealed brass is not.

Bartlett, R. W., "Observations of Vaporization Accompanying Ultra-High Velocity Impact", AFOSR TN 60-327, Institute Metals Explosives Research, University of Utah (January, 1960). K-3-5

This study emphasizes the vaporization and penetration of metals. Jets from shaped charges and discrete particles were used as projectiles. A variety of targets and projectiles were used. The condensed vapors were collected and analyzed quantitatively to determine the ratios of the projectile or jet to the target metal as a function of impact velocity.

Bodner, S. R., and Symonds, P. S., "Plastic Deformations in Impact and Impulsive Loading of Beams", Proceedings Second Symposium Naval Structural Mechanics (1960). K-3-6

A summary of recent experimental work to evaluate the assumptions of dynamic rigid-plastic theory is presented. The need to consider the space and time variation of the yield moment in interpreting experimental results on experiments performed on cantilever beams is shown, and a mathematical model that incorporates these features is discussed.

Broberg, K. B., "Some Aspects of the Mechanism of Scabbing", International Symposium Stress Wave Propagation Materials, Interscience Publishers, Inc., New York (1960). K-3-7

It is shown that scabbing is a fracture phenomenon where delay times play an important part and that the scab thickness can be determined approximately if the relation between stress and delay time for fracture is known. There will be a region of fracture rather than a definite fracture surface. The reasons for fracture delay in ductile materials are given and briefly discussed.

Broberg, K. B., "Studies on Scabbing of Solids Under Explosive Attack", Journal of Applied Mechanics, Transactions ASME, 77, 317-323 (September, 1955). K-3-8

The mechanism of the scabbing phenomenon is discussed both theoretically and experimentally. The experimental method used to determine pressure-time relations on the face of a plate where detonation occurs is a modified-pressure bar. Plane scabbings are obtained by inserting cylinders of explosives in holes in the plate.

Campbell, J. D., and Duby, J., "The Yield Behavior of Mild Steel in Dynamic Compression", Proceedings Royal Society of London, Series A, 236 (1204), 24-40 (1956). K-3-9

Experiments are described in which a mild-steel specimen is subjected to a compressive-impact load. Stress-time curves are obtained and analyzed. Micrographs of specimens after yielding are shown to show the metallurgical mechanism of yielding.

Campbell, W. R., "Determination of Dynamic Stress-Strain Curves From Waves in Long Bars", Proceedings of Society for Experimental Stress Analysis, 10 (1), 113 (1952). K-3-10

A method is presented for experimentally deriving the relation between stresses and strains set up in a long bar by a deformation wave being propagated as a longitudinal-plane wave. Analytical concepts are outlined, and experimental techniques are described in detail. Results of preliminary tests which demonstrate the application of the method are presented for copper bars subjected to longitudinal impact.

Cassity, C. R., "Stress Waves in Solids", Journal of Applied Physics, 31, 1377 (August, 1960). K-3-11

Tests dealing with the effects of stress waves initiated in solids by high explosives or by impacts are discussed. Indications are that stress waves which are initiated solely as compression commonly acquire tensile components which are not due to reflections.

Cottrell, A. H., "Deformation of Solids at High Rates of Strain", Chartered Mechanical Engineer, 4 (1), 448-460 (November, 1957). K-3-12

This article gives a detailed theoretical analysis of the effect of strain rate on the physical properties of metals. Such phenomena as delayed-yield point, increased yield strength, and heat effects as a function of strain rate are given.

Cowper, G. R., and Symonds, P. S., "Strain-Rate Effects in the Impact Loading of Cantilever Beams", NR-064-406, Office of Naval Research, to USN on Contract No. Nonr-562(10); AD 144762. K-3-13

The problem of impact loading of a cantilever beam which exhibits either strain-hardening or strain-rate sensitivity is considered. On the basis of an assumption concerning the mode of deformation of the beam, the motion of the beam is analyzed. The influence of strain hardening and strain-rate sensitivity on the permanent deformation is calculated. In addition, numerical results are presented for the predicted plastic strains and strain-rates within the beam. Finally, directions in which an extension of the analysis is desirable are indicated.

Davids, N., Editor, International Symposium on Stress Wave Propagation in Materials, Pennsylvania State University, June 30-July 2, 1959, Interscience Publishers, Inc., New York (1960). K-3-14

This review covers fifteen papers on current progress in several scientific fields concerned with stresses with high rates of loading, mainly of an impact nature. Specific references to individual papers are presented throughout this report.

Davids, N., "Stress Waves of Penetration in Plates", Interim Technical Report No. 12, Pennsylvania State University, for USA on Contract No. DA-36-061-ORD-465. K-3-15

Scabbing effects in a plate may be analyzed theoretically by assuming elastic stress waves excited periodically at a point-source on its boundary. The usual classical results are inaccurate since the damaging wave is the one penetrating through the plate rather than propagating along it, and the dimensions of the plate in practical applications are just of the order of a wavelength. A more precise foundry-value problem is worked out and resulting axial stress wave distributions for aluminum plates are given.

Davis, C. D., and Hunber, S. C., "An Indentation Test for the Rapid Assessment of the Strain-Rate Sensitivity of Metals", Report (MX) 19/59, Ministry of Aviation, A. R. D. E. (October, 1959). K-3-16

A test is described where a normal impact of a few milliseconds duration of a conically-tipped tungsten carbide indenter on the specimen at impact velocities of 2-30 centimeters per second is used. Comparison of the results of static and dynamic tests give the strain-rate sensitivity of the material.

Davis, E. A., "The Effect of the Speed of Stretching and the Rate of Loading on the Yielding of Mild Steel", Journal of Applied Mechanics, Transactions ASME, 5 (4), A-317-A-140 (December, 1938). K-3-17

In order to investigate the rate of loading on the yielding of mild steel, a machine was designed in which the amount of increase in load per unit time could be held constant regardless of the rate of strain. Results of tests are presented in which the rate of loading for separate tests was changed by a maximum ratio of 1 to 21,000. The effect of rate of loading was studied on four different shapes of test specimens.

De Sy, A., and Deknock, Fr., "Influence of the Speed of Impact in the Impact Test on Grey Cast Irons", Fonderie Belge, 30, pp 8-12 (January, 1960). In French. K-3-18

Tests on cylindrical specimens of three grades of gray cast iron show that impact resistance increases with speed of impact. Therefore, the modulus of impact (ratio of energy required to the volume between supports of the specimen) also increases.

Dewey, J., Breidenbach, H. I., and Gehring, J. W., "Some Observations of Elastic Properties of Solids Under Explosive Loading", Report No. 931, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. K-3-19

The strains and shock fronts in a magnesium alloy subjected to a contact detonation have been determined from flash radiographs. From these the stresses and stress-strain ratios for the compressional and shearing strains at the shock fronts have been computed, using finite-strain theory. The compressional stress-strain ratio exceeds the infinitesimal and increases rapidly with strain. The shearing stress-strain ratio is considerably lower than the infinitesimal and about that predicted from Murnaghan's second-order theory. Much less complete observations on plate and Catalin 61-893 are reported and reduced. Observations on heavier materials give subsonic-shock velocities under very high stresses. In all materials except glass the compression front is markedly curved, indicating a rapid decay of shock strength.

Fehi, R. O., Packer, E. R., and Michael, D. J., "Measurement of Dynamic Stress and Strain in Tensile Test Specimens", Transactions ASME Supplementary, 66, aA-65 (June, 1944). K-3-20

In the investigation detailed in this paper, the tensile strength, the yield strength, and the breakage energy of test specimens (cold-rolled steel and duraluminum) were measured while the specimens were being broken by a force applied at a high rate of speed in a commercial high-velocity-impact testing machine. The dynamic tensile strength, the dynamic yield strength, and the dynamic breakage energy were found to be higher than the static values up to the maximum impact velocities of these tests (100 fps). The paper contains a presentation of some results of these tests, a description of the technique used, and a description of the analysis used.

Foeppl, L., "Slow Motion Pictures of Impact Tests by Means of Photoelasticity", Journal of Applied Mechanics, Transactions American Society of Mechanical Engineers, 71, 173-177 (June, 1949). K-3-21

Moving pictures are presented showing the stress fluctuation in beams due to the impact of a hammer. Both elastic and plastic conditions are shown. The maximum camera speed was 3020 frames per second.

Greenfield, M., and Habir, E. T., "High Speed Compression Tests on Copper", Journal of Applied Physics, 18 (7), 645-650 (July, 1947). K-3-22

Dynamic shortening of one-half-inch long copper cylinders is achieved by striking them with a hardened steel projectile at high velocities. The average strain rate was about 1200 inches per inch per second. Energy per unit volume absorbed by the copper is plotted against strain. A true-stress-logarithmic-strain curve is computed. This curve is compared with a similar curve derived from high speed tests on copper in tension.

Hawkyard, J. B., and Freeman, P., "Stress-Strain Characteristics of Metal at High Rates of Strain", British Journal of Applied Physics, 7 (1), 3-4 (January, 1956). K-3-23

This paper describes an apparatus and experimental techniques by means of which the compressive stress-strain relations of various metals have been determined at rates

of strain from 100 to 600 inches per second. The results were compared on the basis of the so-called "friction hill" equation.

$$P = Y\,[1 + (2ua/3h)]$$

where P is the mean pressure on the specimen
Y is the yield stress corresponding to the current compressive strain
u is the coefficient of friction between the specimen and the die
a is the radius of the specimen
h is the height of the specimen.

Parker, E. R., and Ferguson, C., "The Effect of Strain Rate Upon the Tensile Impact Strength of Some Metals", Transactions of the American Society for Metals, 30 (1), 68-85 (March, 1942). K-3-24

High-velocity tension-impact tests were conducted on a number of metals and alloys. The energy absorbed during rupture and the elongation and reduction of area of the fractured bars is reported. Most materials tested absorbed more energy at higher impact velocities. However, there were exceptions which serve as warnings against drawing general conclusions about the effect of velocity on impact strength.

Prandtl, L., "Ein Gedankernmodell Zur Kinetischen Theorie Der Festen Kopper", Zeitschirift fur Angewandte Mathematik und Mechanik, 8 (2), 85-106 (1928). In German. K-3-25

The article discusses the possible construction of a model to show movement effects of the molecular planes in a material subjected to deformation under varying rates of stress application. The model consists of considering two straight edges held by an elastically supported mass element. The one shifts alongside the other with a force-field of attraction and repulsion. The form change of one of the bodies is then considered on the basis of hysteresis, elastic resultants, and dependency of flow-stress on the flow-velocity. Theoretically predicted quantities are presented for the temperature dependency from room temperature to elevated temperatures. Results were obtained through examination of the behavior of a viscous fluid under the influence of temperature and pressure.

Riparbelli, C., "On the Relation Among Stress, Strain, and Strain Rate in Copper Wires Submitted to Longitudinal Impact", Proceedings Society for Experimental Stress Analysis, 14 (1), 55-70 (1956). K-3-26

A series of exploratory tests of tensile impact on copper wires is presented to show that the elastic component of a stress wave moves at a constant velocity regardless of the amount of plastic deformation. The method consists of dropping a weight on copper wire. Bright tin spots on wire are photographed with high-speed photography to observe motion of the stress waves.

Schwartzberg, F. R., "Effects of High Strain Rates and Rapid Heating on the Tensile Properties of Titanium Alloys", Light Metal Age, 17 (12), 11-12 (February, 1959). K-3-27

Experimental findings indicated an increase in strain causes an increase in strength most pronounced at high temperatures. A general decrease in ductility and no appreciable change in modulus of elasticity was noted. The effect of increasing temperature was found to be a decrease in strength and elasticity.

Shanley, F. R., "Analysis of Stress-Strain-Time Relations From the Engineering Viewpoint", Presented at the Second Symposium on Plasticity, Brown University, April 4-6, 1949; Revised September, 1951, The Rand Corporation, Santa Monica, California. K-3-28

Stress-strain diagrams for various loading histories are developed by a step-by-step process in which elastic action is assumed to be instantaneous and reversible, while plastic action is assumed to occur at constant stress, as a function of stress, time, and the extent of plastic straining. The plastic-flow (or generalized-creep) curves are shown to be a suitable basis for the analysis of stress-strain-time relationships as affected by rate of loading, temperature, and combined stress conditions. Some of the engineering applications of this type of analysis are illustrated. Also discussed are Poisson's Ratio in the plastic range, cohesive failures during shear slip, and the octahedral shear stress as a basis for theories of plasticity and failure.

Smith, R. C., Pardue, T. E., and Vigness, I., "The Mechanical Properties of Certain Steels as Indicated by Axial Dynamic Load Tests", Society Experimental Stress Analysis Proceedings, 13 (2), 183 (1956). K-3-29

Results of an investigation of the influence of strain rate on the shape of stress-strain curves are given. Dynamic yield points were found to be greater than static yield points. An attempt is made to correlate delay times for yielding under constant strain rates with values obtained in constant stress tests.

Taylor, D. B. C., "The Dynamic Straining of Metals Having Definite Yield Points", Journal of the Mechanics and Physics of Solids, 3 (1), 38-46 (1954). K-3-30

Strain rate during nonuniform yielding of metal under repeated dynamic loading is analyzed. It is deduced that the time-yield stress relationship appears to be described better by a "delay period" than by a simple strain-rate phenomenon. The criterion for dynamic yield is discussed.

Turnbow, J. W., and Ripperger, E. A., "Strain-Rate Effects on Stress-Strain Characteristics of Aluminum and Copper", Proceedings Fourth Midwest Conference Solid Mechanics, University Press, Austin, 415-440 (September, 1959). K-3-31

Disadvantages of direct and indirect methods used for obtaining stress-strain relations at high strain rates are discussed. A dynamic loading device designed to overcome some difficulties is described. Effective elastic modulus of both materials seems to decrease with increasing strain rate.

Vasilyev, L. I., Bylina, A. S., and Zigrelennikova, M. P., "On the Effect of Change in Deformation Rate on Plastic Deformation", Doklady Akademii Nauk SSSR, 90, 767 (1953) in Russian; National Science Foundation Translation No. 138 (December, 1953). K-3-32

Increase in deformation rate apparently results in a qualitative change in the spatial distribution of deformation distortions and in an increase of their "variety". It is shown that the current value of the stress in the general case is not a single-valued function of the instantaneous values of deformation, of the deformation rate, or of temperature.

Winslow, G. H., and Bessey, W. H., "High Speed Compression Testing of Copper Crusher Cylinders and Spheres", NDRC Report No. A-324, OSRD Report No. 5039 (April 24, 1945); ATI 18764. K-3-33

This report deals with measurements of the speed effect in small copper cylinders and spheres. Rates of strain lying approximately in the range from 400 to 2000 inches per inch per second are possible with a rotating flywheel device. Rates of strain below the 400 inch per inch per second level were also investigated. A correlation between dynamic strain and static strain when measured by the height of the crushed specimens was obtained.

Lange, E. A., Crooker, T. W., and Klier, E. P., "Tensile Properties of Explosively Formed Mild Steel Plate", NRL Report 5819, U. S. Naval Research Laboratory, Washington, D. C. (September 18, 1962). K-3-34

The strains produced by the explosive forming of a metal plate result from dynamic body loads. Consequently, the strains will vary at different locations on a plate supported by a die with a central hole since the variation is a result of the way in which the kinetic energy produced by the explosion is dissipated in the plate. In the present investigation four samples of 1/2-inch-thick mild-steel plate were explosively formed through a central-hole die in the circular bulges. Specimens from the bulge, the die-edge region, and the plate edge were taken from each plate and stress-strain relationships were determined from these specimens.

At all locations on each plate the increase in both yield strength and tensile strength is significant. The explosively induced strain, however, has a greater effect on yield strength than on normal tensile strength. The maximum potential increase is approximately 150 per cent, in yield strength. The forming strain at the maximum levels of strength causes only a 30 per cent decrease in reduction in area. For the mild steel plates used in this investigation, high values of forming strains increased the nominal tensile strength from 50,000 psi to 75,000 psi. It was found that the terminal strain from explosive loading is equal to the terminal strain in a conventional tensile test. Also residual macrostresses in explosively-formed mild steel are nil.

Zaitsev, G. P., and Bondarev, Iu. E., "Temperature Mosaics and the Instantaneous Secondary Stresses in Impact Deformation of Two-Phase Metals", Fizika Metallov i Metallovedenie, 3 (1), 139 (1956). K-3-35

Calculations of instantaneous secondary stresses, developing when the phases or various structural constituents differ with respect to their resistance to plastic deformation, are given.

Zener, C., and Hollomon, J. H., "Effect of Strain Rate Upon Plastic Flow of Steel", Journal of Applied Physics, 15 (1), 22-32 (January, 1944). K-3-36

An experiment has been designed to check a previously proposed equivalence of the effects of changes in strain rate and in temperature upon the stress-strain relation in metals. It is found that this equivalence is valid for the typical steels investigated. The behavior of these steels at very high rates of deformation may, therefore, be obtained by tests at moderate rates of deformation performed at low temperatures. The results of such tests are described. Aside from changing the isothermal stress-strain relation, an increase of strain rate tends to change the conditions from isothermal to adiabatic. It is found that at low temperatures, the adiabatic stress-strain relation in the plastic range is radically different from the isothermal, having an initial negative rather than a positive slope. This initial negative slope renders unstable homogeneous plastic deformation.

Zernow, L., and Simon, J., "Plastic Behavior of Polycrystalline Metals at Very High Strain Rates", Physics Review, 91 (1), 233 (July 1, 1953). K-3-37

The behavior of a variety of polycrystalline metals at strain rates of the order of $10^4$ seconds is being studied. Face-centered-cubic metals, copper, nickel, aluminum, and silver, have been found to deform plastically quite readily with relatively small differences in their comparative behavior. Body-centered-cubic materials like iron have been observed to undergo early fracture as have, also, members of the close-packed hexagonal family.

Campbell, J. D., "An Investigation of the Plastic Behavior of Metal Rods Subjected to Longitudinal Impact", Journal of the Mechanics and Physics of Solids, 1 (2), 113-123 (1953). K-3-38

A dynamic stress-strain relation is obtained for an aluminum alloy. An ST-4-type strain gage is mounted on a rod-type specimen. Successively larger impacts are applied to a steel rod then transmitted into the specimen to obtain a stress-strain curve. The effect of the steel rod is to increase the applied stress and also to separate the flexural and longitudinal components due to differences in velocity of propagation.

Allison, E. E., and Watson, R. W., "Explosively Loaded Metallic Cylinders", Journal of Applied Physics, 31 (5), 842-845 (May, 1960). K-3-39

Recent experiments using thin-walled metal cylinders internally loaded with high explosives have been performed in an effort to show that the casing velocity vector

bisects the angle formed by the expanding cylinder and the undisturbed portion. This relation, first derived by Sir Geoffrey Taylor, can be expressed by the equation $\delta = \theta/2$ where $\delta$ is the angle between the velocity vector and the normal to the undisturbed casing, and $\theta$ is the angle formed by the normals to the moving and undisturbed portions of the casing. This paper is an attempt to verify this relation by experimental methods. The experimental observations proved to be in good agreement with $\delta = \theta/2$.

Smith, R. C., "Studies of the Effect of Dynamic Preloads on the Mechanical Properties of Steel", NRL Report 5323, U. S. Naval Research Laboratory, Washington, D. C. (May 29, 1959); PB 151685. K-3-40

Specimens of a low-carbon steel have been subjected to dynamic loads in an adaption of the Taft-Pierce Shock Machine for electronic devices. The intensity of the load was varied; some specimens were subjected to elastic shocks involving loads in excess of the static yield stress, while in others gross yield was initiated. These specimens were then aged for a short time at temperatures ranging from 68 to 250 F and then retested dynamically or in static tension. Upper- and lower-yield stresses and the inelastic microstrain which preceded gross yield on the retest have been used to evaluate the extent of damage and recovery.

Duwez, Pol E., Wood, D. D., and Clark, D. S., "The Effect of Stopped Impact and Reflection on the Propagation of Plastic Strain in Tension", Office of Scientific Research and Development, NDRC, Div. 1, California Institute of Technology, Pasadena, California (November, 1942); ATI 24942. K-3-41

The comparison of theoretical computations of strain distribution and stress-time relations with the experimental results for tension-impact tests indicates that the von Karman theory, and the Taylor theory of the propagation of plastic waves in metals, and the methods of computing the reflection and stopping of these waves are substantially correct. Irregularities found in the curves are indicative of the steps predicted by von Karman rather than of the smooth curve given by Taylor's approximate solution. In general, the strain distribution in specimens of finite length subjected to tension impact can be predicted with reasonable success from an accurate stress-strain diagram.

Wood, D. C., Duwez, P. E., and Clark, D. S., "The Influence of Specimen Dimensions and Shape on the Results of Tensile Impact Tests", California Institute of Technology, Pasadena, California (December, 1943); ATI 25017. K-3-42

A study was made on the influence of specimen length, diameter, and cross-sectional shape on tensile-impact tests. A detailed discussion is given of the effect of the ratio of length to diameter, the effect of size in geometrically-similar specimens, and the influence of cross-sectional shape. The results show that the effect of velocity on the tensile properties of metals is independent of both the dimensions and the cross-sectional shape of the specimen. Furthermore, the critical velocity is not altered by these variables.

Rinehart, John S., "The Behavior of Metal Under High and Rapidly Applied Stresses of Short Duration", NAVORD Report, U. S. Naval Ordnance Test Station, Inyokern, California (September, 1949); ATI 76467. K-3-43

Some of the effects produced by detonating explosive charges in intimate contact with metal plates, rods, and tubes resulting in high and rapidly applied stresses are described. The principal observable effects are the fracturing of the metal due to a tensional stress produced as the result of the reflection of a high compressional-stress wave at a free boundary, the fracturing of the metal due to high hydrostatic pressure resulting from extremely rapid compression of the metal, and a simple low-order permanent strain similar to that observed in slow compression tests. Further work is to be conducted on the study of these effects; the need for theoretical studies along these lines is indicated.

Filbey, Gordon L., Jr., "Deformation Waves in Annealed Aluminum Rods Undergoing High Velocity Impact", thesis written as partial fulfillment of requirements for Ph.D. degree. Johns Hopkins University, for USA on Contract No. DA-36-034-31x4992. 509-ORD-3104RD (September, 1961). K-3-44

This thesis describes experimental work done by the author in one-dimensional plastic-wave propagation. By using the impact velocities which produce a 12 per cent compressive-strain wave he found that a cubic stress-strain law describes the initial propagation of the strain wave during the first 9 $\mu$sec through the first one-half-diameter region of the bar from the impact face. Then there is a transition to a quadratic stress-strain law [ $(5.80 \times 10^4)\ \Sigma\ 1/2 = G$ for aluminum]. The cubic relationship is derived from the equations:

$$(1)\quad G = \beta\epsilon^{\alpha} \text{ and } (2)\ C_p\ (\Sigma) = \sqrt{\frac{\beta\alpha}{\rho}}\ \Sigma\ \frac{\alpha - 1}{2}\ .$$

From experimental data and given values, it was determined that $\alpha = 0.326$ and $\beta = 18.9 \times 10^4$ psi or a nearly cubic stress-strain law.

Filbey, Gordon L., Jr., "Deformation Waves in Annealed Rods Undergoing High Velocity Impact", Technical Report No. 8, Johns Hopkins University for United States Army on Contract No. DA-36-034-21x4992. 509-ORD-3104RD (September, 1961). K-3-45

An experimental study is made of the plastic wave initiated by 3000 inches per second constant-velocity impact in annealed aluminum rods. Particular attention is focused on the behavior of the deformation wave in the first one-half-diameter region from the impact face. In this region, a nearly cubic stress-strain law is found to be operative for the first 9 microseconds, which with the Karman-Taylor theory describes the initial development of the deformation wave. Maximum observed strain rates are to the order $3 \times 10^4$ inches per inch per second. A transition to the quadratic law reported by Bell is then found operative over the remainder of the rod, using the Karman-Taylor theory. The use of the quadratic law in the Karman-Taylor theory may now be extended to the 3000 inches per second impact-velocity region to describe the general character of plastic-wave deformation of annealed aluminum.

Dieter, G. E., "Strain-Rate Effects in Deformation Processing", Paper presented at the Ninth Sagamore Ordnance Materials Research Conference on Fundamentals of Deformation Processing, Raquette Lake, New York, August 28-31, 1962. K-3-46

The literature on the strain-rate dependence of the mechanical properties of metals is reviewed with respect to how this applies to deformation processing where velocities of 20 to 3,000,000 inches per minute may be encountered. Strain rate has three effects in metalworking. Increasing strain rate increases the basic resistance of the metal to deformation. Opposing this is the fact that at high-deformation velocities the heat of deformation cannot be dissipated within the time of the event. The resulting temperature rise leads to a decrease in deformation resistance. High-deformation velocities also alter the frictional conditions at the metal-tool interface, usually in the direction of improved lubrication so long as a film can be maintained. The new high-energy-rate forming techniques are described and discussed. The relative advantages and disadvantages of the pneumatic, electrical, and explosive methods are considered.

Backman, Marvin E., "Propagation of Compressive Stresses Through a Plastically Deforming Material", NavWeps Report 7896, NOTS TP2896, U. S. Naval Ordnance Test Station, China Lake, California (April, 1962); AD 275500. K-3-47

This report considers the application of this material description from a previous report to those problems of impact and explosive phenomena in which plane-wave analysis are applicable. The material description is first used in a discussion of the shock conditions in the material and the continuous conditions behind the shock. The general problem of shock-wave interaction with the continuous motion behind the shock is then considered, and the particular approximate method of treating these interactions is derived. A numerical solution is obtained for the impact at a plane surface with a second body of the same material. The material selected is aluminum for which the required data are available. The calculations were carried out by a 7090 IBM digital computer and the results are given in graphical form.

<u>Cross References.</u>

B-4-11 Describes how dynamic stress-strain curves obtained experimentally (for annealed copper and aluminum) may be computed directly from theory using information supplied by the static stress-strain curve.

B-4-12 Discusses optical method for measuring strain.

B-4-13 Describes how propagation velocities, maximum strain, and energy considerations for large-amplitude compression waves in annealed aluminum agree with predictions of the static stress-strain curve.

B-4-14 Studies the unloading phenomenon for two identical specimens in free flight collision. There is agreement with the strain-rate theory of plastic-wave propagation.

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| B-4-19 | Covers stress-strain relations in connection with longitudinal plane waves. |
| B-4-20 | Deals with small cylinders of lead which were fired at various velocities The resulting deformation is used in deducing the stress involved. |
| D-1-3 | Presents information on the influence of rate and degree of deformation and of temperature on the stress causing deformation for alloy TsAM9-1,5. |
| E-2-10 | Describes a new reflected-light technique for making dynamic pressure-compression measurements in the region between existing dynamic measurements and the elastic region. |
| F-1-0-1 | Presents the general theory of the small deformation elastic response of spherical shells. |
| F-1-0-2 | Gives analytic solutions to linear and small-deflection equations of motion for shell materials which exhibit various degrees of strain hardening. |
| F-1-0-39 | Discusses forces and ductility to be expected when high or low explosives are used in explosive forming. |
| F-1-7-6 | Correlates uniaxial and biaxial strain rates with ductility and temperature. |
| F-3-0-10 | Discusses the response of metals to high-velocity forming. |
| F-3-6-2 | Determines feasibility of using an impact extrusion technique for determining the influence of strain rate on the strengthening effect of ausforming. |
| J-3-7 | Presents elastic analysis of plates under plane stress and plane strain. |
| K-0-10 | Describes relation between yield point, maximum elastic deformation and rate of deformation. Also gives shape of stress-strain curve. |
| K-1-32 | Investigates effect of strain rate on the strength of magnesium alloys. |
| K-1-36 | States that slope of the stress-velocity curve for dislocations might be determined from measurements of rate sensitivity. |
| K-1-48 | Describes technique for applying uniform compressive stress and measuring time delay before plastic yielding. |
| K-2-16 | Presents development of strain and torque for several materials at constant and changing rates of deformation and at constant and changing temperatures. |

## AUTHOR INDEX

## AUTHOR INDEX
(Continued)

## AUTHOR INDEX
(Continued)

## AUTHOR INDEX
(Continued)

## AUTHOR INDEX
(Continued)

## AUTHOR INDEX
(Continued)

AUTHOR INDEX
(Continued)

## AUTHOR INDEX
(Continued)

## AUTHOR INDEX
(Continued)

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